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Intelligent Systems:
Annotated Bibliography and Survey
Part I. Systems with Intelligent Controllers

A. Meystel

U.S. DEPARTMENT OF COMMERCE
Technology Administration
Intelligent Systems Division
National Institute of Standards
and Technology
Gaithersburg, MD 20899

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Donald L. Evans, Secretary

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Phillip J. Bond, Under Secretary for Technology

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Arden L. Bement, Jr., Director

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Intelligent Systems
Annotated Bibliography

Part I. Systems with Intelligent Controllers

Abstract

In Part I of this report, a place of Intelligent Control in the variety of systems is discussed. In many cases it amounts to transforming the system into an *intelligent system*. Intelligent Systems employ principles of information generalization, semiotic closure and multiresolutional (multigranular, multiscale) representation. The annotated bibliography and survey of literature demonstrate that the number of devices and principles that can be associated with intelligent control much exceeds those applied in three broadly used components: fuzzy representation, neural networks, and genetic algorithms. Using these components only doesn't specify all variety of possible technical solutions. A broad multiplicity of existing intelligent systems demonstrate human-like capabilities of dealing with uncertainties: like in expert system and knowledge bases equipped controllers, multi-agent behavior based controllers, game-theoretic controllers, and others.

This annotated bibliography and survey prove that intelligent controllers can be better recognized by taking in account the computational tools they use and by the architecture, within which these tools are engrained. This issue will be addressed in more detail in the second part of the survey.

Keywords

intelligence, intelligent control, intelligent system, generalization, multiresolution, multigranular, multiscale, fuzzy, neural, genetic, expert system, agent, multi-agent, behavior, game-theoretic control, architecture, computational tool

Title:

Intelligent Systems
Annotated Bibliography

Part II. Systems with Learning and Autonomy

Abstract

Part II is concentrated upon the intelligent systems equipped with subsystems that provide for a comparatively highly sophisticated faculties of intelligence: learning and autonomy. It explains general Concepts of Learning and demonstrates that by using the techniques of learning automata, the inductive techniques of learning can be introduced and explored. Implicitly, learning algorithms allude to the mechanisms of generalization, and fuzzy methodologies of representation can serve as an appropriate computational tool. The algorithms of learning from experience, identification and diagnostic greatly benefit from the learning techniques. Once equipped with a system of learning, the intelligent system demonstrate qualities of adaptivity.

The survey familiarizes readers with reinforcement leaning in a variety of applications. Comparatively simple cases of learning are utilized for pattern recognition. Frequently they incorporate neural networks and genetic algorithms. Hierarchical learning systems are applied for decision making and planning. Once equipped by these tools, the intelligent system demonstrates properties of autonomy.

Keywords

intelligent system, learning, autonomy, adaptivity, learning automata, inductive principle, generalization, fuzzy, identification, diagnostics, adaptivity, pattern recognition, hierarchical learning, decision making, planning

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Table of contents

Part I

Part II

I.1 Theory of Intelligent Control

1.1 The Essence of Intelligent Control and Control Architectures

Two major points of view are prevalent in the literature related to Intelligent Control. One view is that Intelligent Control is supposed to demonstrate properties and features typical for human intelligence. According to this point of view, the devices that are utilized are irrelevant. Most important is the ability of a control system to make decisions in uncertain situations to the benefit of the system specified by a designer.

The second point of view links the concept of intelligent control to utilizing a number of concrete devices including Fuzzy Logic (FC), elements and systems, Neural Networks (NN), and Genetic Algorithms (GA).

The survey of literature shows that the number of devices and principles that can be associated with intelligent control much exceeds these three concrete components: FC, NN, and GA. Also, the first view doesn't specify all varieties of possible technical solutions. A broad multiplicity of technical solutions can fit within the requirement of demonstrating human capabilities for dealing with uncertainties. Some examples of such technical solutions are: expert system and knowledge bases equipped controllers, multi-agent behavior based controllers, and others.

In Figure 1, the three major theoretical techniques typical for systems with intelligent controllers are demonstrated to be various facets of multiresolutional computational methodologies applied to solving problems of control represented in the multiresolutional state space. Fuzzy systems enhance the original tessellatum of discretized space as required; NN is a device that provides for fuzzification in the vicinity, and genetic algorithms apply search techniques to a couple of adjacent levels of resolution.

This survey proves that intelligent controllers can be better recognized by taking into account the computational tools they use and by the architecture within which these tools are engrained. This issue will be addressed in the concluding part of the survey.

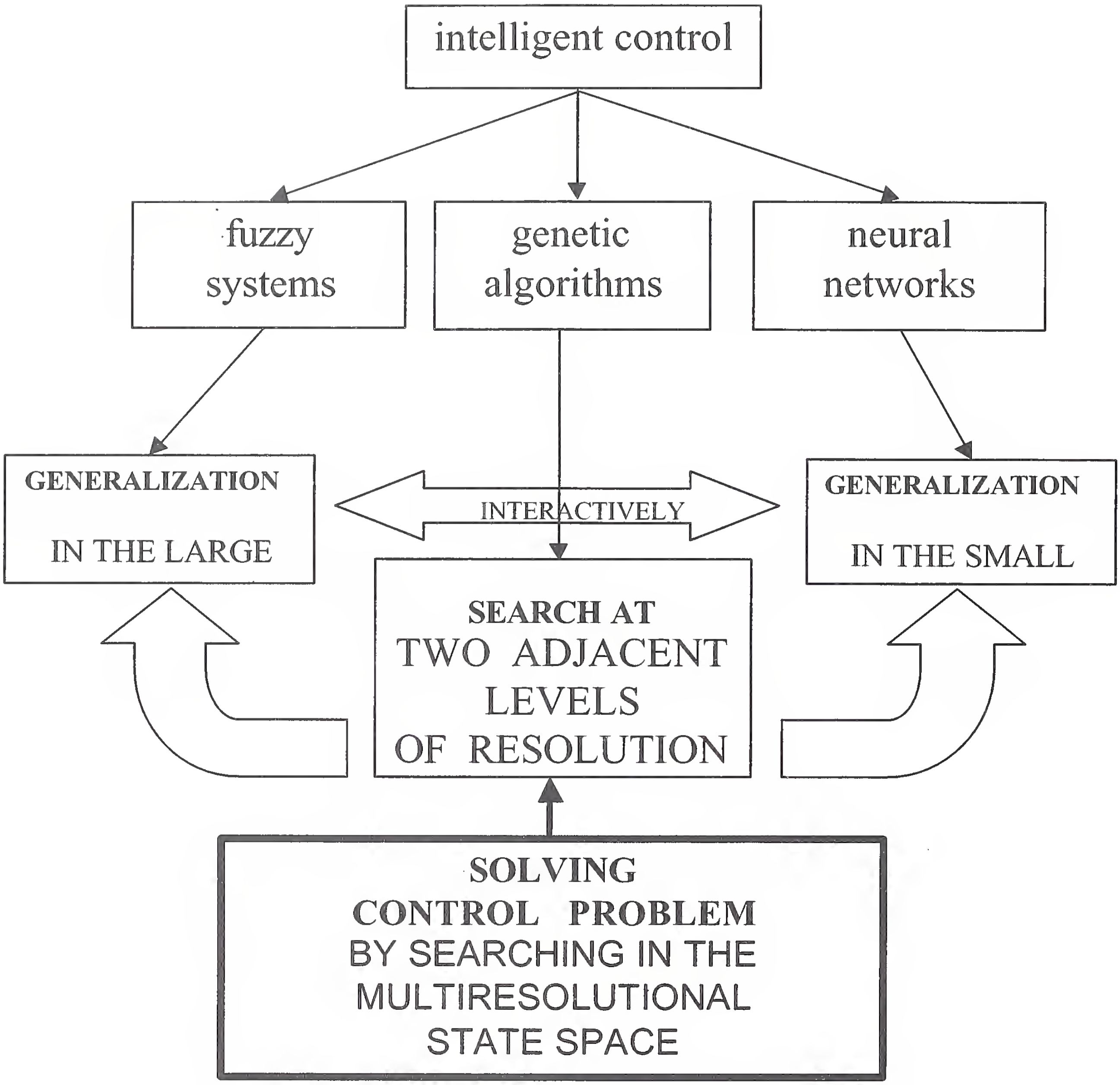

Figure 1. The existing theoretical techniques are unified by the common approach to representation

Classical works in Intelligent Control by G. Saridis tend to organize a control system as a three-level hierarchy: management, coordination and execution levels are accepted as a template for control architecture. In practice of intelligent control, it was understood that the number of levels of control depends rather on a size of problem.

In Figure 2, the multiagent system is demonstrated. This is a group of autonomous mobile robots interpretable for both military and civillian outdoor scenario of realization. Its control is organized as a hierarchy of levels granularity level (levels of resolution, levels of scale). Three levels introduced by G. Saridis can be discovered at each level of resolution [372]. These levels can also be interpreted as the modules of Job Assignment (JA), Planning (Pl) and Execution (Ex) introduced within Real Time Control Systems (RCS) methodology [494, 495, 971].

1.2 Control Laws Applied

The concept of Intelligent Control made the issue of "control architecture" the major issue of control theory and engineering (see Section 1.5). Before this, the main question was: "What is the control Law?" An overview and comparison of a multiplicity of control laws is given in [1]. The feeling that all control laws target the same end is conveyed in [2], where Kalman Filter is explained as a particular incarnation of the feedback compensation of the negative feedback compensation under a definite premise of estimating an error. This view is conformed in [3], where numerous nonlinear controllers are discussed. The concept of "feedforward contro" is not even discussed. Thus, "planning" is not even contemplated..

Actually, the abstract discussion of control laws and abstract introduction of general control solutions seems to be not very productive in a contemporary paradigm of Automatic Control. All control cases surprisingly resemble the concept of the PID error compensating controller, and only our attitude toward the gain assignment is being changed. It is more typical for the present paradigm to consider control laws to be a part of a broader "control strategy" for the overall system. In [4] and [5], control laws are considered to be a part of much broader control strategy formulated for the machine as a whole. In some cases control laws are devised based upon more theoretical premises. In [6] the closed-loop control law is formulated in terms of forming the "pole attracting" zone.

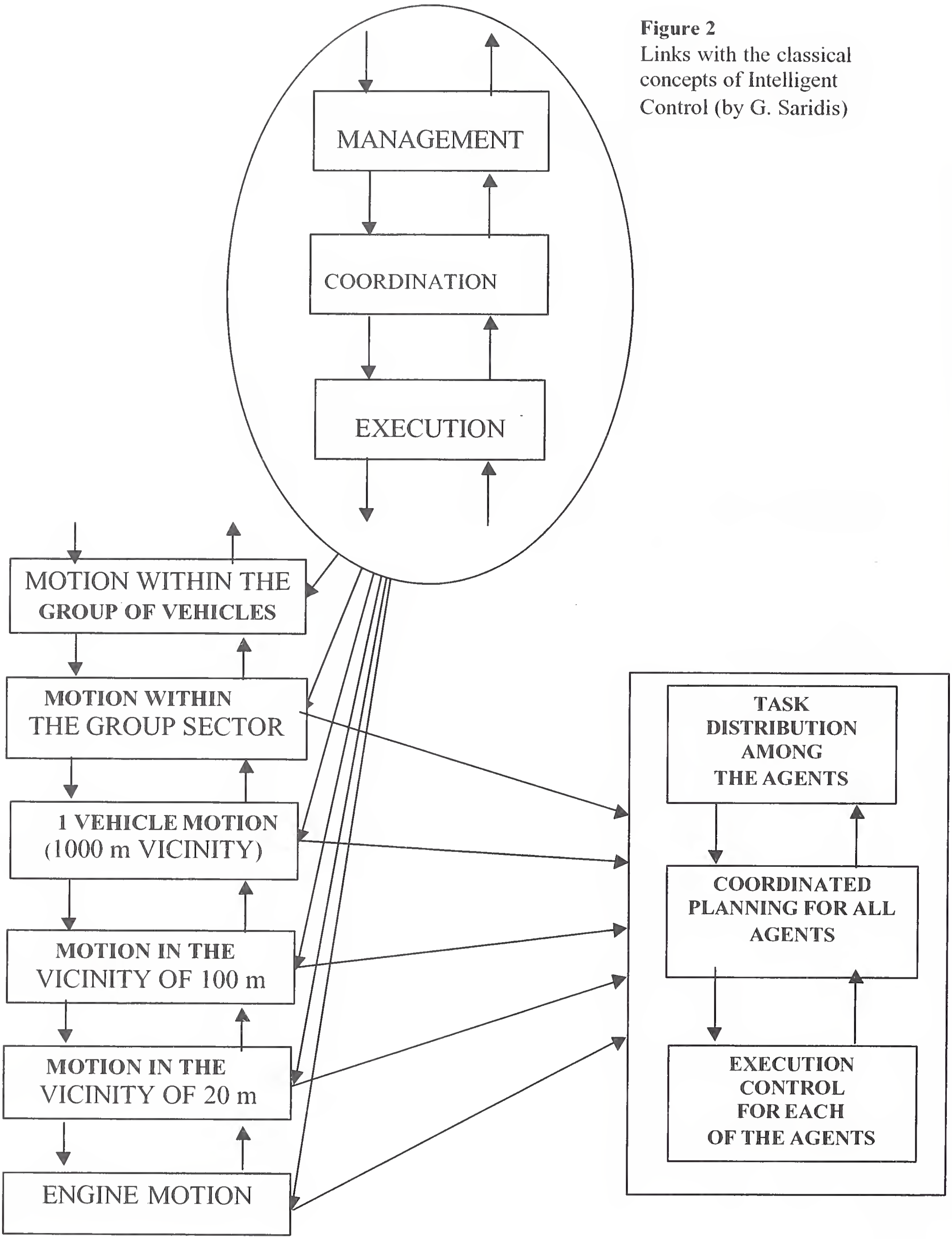

Figure 2
Links with the classical concepts of Intelligent Control (by G. Saridis)

1.3 Fuzzy Logic Controllers

It becomes obvious that the fuzzy logic controller (FLC) belongs to the domain of the intelligent controllers because it employs the concept of changing resolution for the purposes of achieving the required control performance. In the fuzzy logic controllers described in [7] and [8] the fundamental transformation presumes moving input information from the high resolution domain into the low resolution domain by using the tool of "fuzzyfication". Fuzzyfication plays the role of generalization because it searches for adjacency, focuses attention, and groups. The fuzzy logic controller contains control mappings only for generalized information at low resolution. When the required control action is found, this low resolution recommendation should be "instantiated" or moved to the domain of high resolution. This is done by the virtue of "defuzzyfication".

A similar process is described in [9]. For the fuzzy logic controller, the center feature is having input and output information at higher resolution while using control mapping at a lower resolution. Various control laws can be applied in this setting, e.g., PI and PD laws are illustrated in [10]; many other effective configurations can be found in [11]. Thus, papers on fuzzy logic controllers explore various properties of an intelligent controller with two levels of hierarchy. The issue of stability for the two level hierarchy is addressed in [12], [13], [14]. The details for computing variables at low resolution are discussed in [15].

Since fuzzy logic controllers perform generalization anyway (for the sake of fuzzyfication), they have some advantages in control systems with learning: it is known that learning requires generalization [16] (for more see Part II of this report). We can see that the feature of recomputing information to lower resolution by the virtue of generalization is an intrinsic property of each fuzzy logic controller. It makes it a natural candidate for using neural networks as a component. In this case, not only can we re-compute variables to the level of lower resolution where the rules are stored, we can learn these rules on-line. How to do that is illustrated in [17].

Modeling of all processes, characteristic of FLC, is reported in [18]. The laws of generalizing of high resolution information to the lower level of resolution are specified in [19].

1.4 Neural-Net Based Controllers

Neural Networks turned out to be a natural tool for moving information from higher to lower level of resolution. An example of a two-level controller similar to the one presented in [17] is given in [20]. The inverse procedure of moving variables from the lower to the higher level of resolution (defuzzyfication) can be also performed by a simple neural network [21]. This application of neural networks already became a standard (see [22]).

There are several conceptual schemes that characterize the way NN are applied in controllers (including Albus' CMAC, Grossberg's adaptive resonance devices, etc.). All of them are described in Part II, Section 8 of this report.

1.5 Expert System Based Controllers

In many cases the amount of measured information is not sufficient for using formal methods of fuzzyfication and defuzzyfication. In these cases we are unable to use

FLC techniques. Expert systems are used to make a judgement concerning generalizations and rules to be applied at the lower resolution [23]. An example of using an expert system for the real time control of a dynamic process is given in [24]. The advantages of these simplified methods are clear when we compare the required effort with those presented in a complete mathematical model [25].

1.6 Hybrid Logic/Analytical Controllers

Hybrid controllers are defined as multilevel control systems in which lower levels of resolution are formulated in the terms of the logic based (IF-THEN rules based) controllers, while the higher resolution levels are analytical controllers (e.g. PID controllers, Kalman filters, etc.). This is how hybrid systems are described by the organizers of the regular meetings dedicated to these areas: "hybrid systems are models for networks of digital and continuous devices in which digital control programs sense and supervise continuous and discrete plans governed by differential or difference equations" [674].

Hybrid controllers, as a research area, have attracted many strong mathematicians since the very boundary between the discrete and continuous control is under consideration. They are related to the area of intelligent control since they explore many levels of resolution, employ generalization of information from level to level, and confirm computational complexity reduction [26-35.]
It is customary for a domain of hybrid controllers to use and further explore the automata formalism as a control-theoretical tool [36-37].

In [38] a hybrid controller is specified, in which the lower level of resolution is represented by an FLC controller, and the higher level of resolution utilizes integral-derivative control. The term hybrid doesn't necessarily presume the joint use of logical and analytical control tools; joint use of different control principles evokes utilization of the term "hybrid" in many other cases, too. Several examples of using this term are given:

- In 1986 M. De Lassen developed an analysis for the hybrid controller, which is defined as a joint functioning of controllers working at various frequency of sampling [818]. The author considers his work further development of the results of K. Narendra and I. Khalifa [819].
- In 1990 Y.-H. Chen and S. Pandey described a hybrid controller for robot manipulators, in which the term hybrid is understood in a sense that it combines the use of both cone-bounded uncertainty and quadratically–bounded uncertainty for controlling the position and force simultaneously under conditions of an imperfect modeling, realistic friction, payload change and external disturbances [675].
- J. C. H. Chung and G. G. Leininger have developed a controller that compensates jointly for deviations in several variables. This is why they called it a hybrid controller. Among the variables are force and position, and among the factors that are taken care of are the task location, dynamic friction, load variations, and others [820].
- In 1995, C. Kwan presents [676] a theoretical analysis for the hybrid controller for manipulators where the term hybrid is understood as a joint force position controller (as it was understood in [675], too).
- L. R. Medsker defined hybrid intelligence systems that combine several AI technologies to perform better than their individual components would do alone [660].

- In 1996 M. Vukobratovic and O. Timcenko described a hybrid controller for a biped locomotion robot where hybrid is understood as combining a traditional model-based and fuzzy logic based control techniques [677].
- In 1998 J. -S. Liu and S. -L. Chen outlined a theory for the hybrid control of a constrained robot where the term hybrid reflects the duality of having one part of the controller responsible for motion while another part is responsible for forces.

1.7 Behavior-Based Controllers

Behavior based control employs the concept of superposition of the activities of multiple controllers working simultaneously, each providing for a separate type of behavior. Methodologically, behavior-based control evolves from traditional AI, as shown in [888] and, as many other AI-related techniques, is motivated by intuition rather then by explicit analytic proof.

From the control theory point of view the idea is rather straightforward and requires an introduction of the "importance factors" that determine a relative contribution of each control activity in a different situation. For artificial intelligence the view seemed to be a rather novel approach to constructing an architecture of intelligence. Even within behavior oriented methodology of control, the hierarchies are useful for selecting the action [347, 40]. Shaping reactive behaviors in unstructured environments are described in [886]. Generation of subgoals can be done by using a simple neural network solution, as in [529], and by local optimization as in [887].

This is an example from [39] below. Instead of arranging the controller from a mobile robot as a system with a representation upon which a planner develops a trajectory to follow, and an executor is trying to track it, a behavior based robot is constructed as follows: "...several modules would be implemented corresponding to the different competencies necessary to the task: a module for recognizing and going through doors, a module for wall following..., a module for obstacle avoidance..., and so on. All of these modules operate in parallel. A simple arbitration scheme... suffices to implement the desired priority scheme: the obstacle avoidance modules always have priority over going through doors which has priority over wall following. This robot doesn't plan a course of action. However from an observer's point of view it will appear to operate in a systematic rational way."

It is possible to show how a robot, without representation and with superposition of behaviors, can be easily deceived by the environment. Nevertheless, for simple cases this vision was appealing and generated numerous research results, like in [40]. In [44] a case of wall following is described where a genetic algorithm is used for improving the decision making process. The superposition of behaviors can be implemented together with NN-based elements of learning [41] (for more, see Part II, Section 8).

It was also evident that superposition of behavior can't satisfy requirements of functioning in the realistically complex cases, nevertheless the idea was appealing because of the resemblance between "behaviors" and basic reflexes of living creatures [42]. Later it became clear that superposition of behaviors doesn't need to substitute planning: it can be added to the RCS-like hierarchical planning as a nice locally useful feature [43]. As a local feature the behavior based "skills" can learn and evolve [44, 45].

The contemporary behavior-based control architecture explicitly comprises reactivity, planning, deliberation and motivation that are supposed to respond not only to the external situation, but also to the list of its needs, and results of cognitive processes for synthesizing the action [885]. The techniques of behavior-based control formation can be beneficial for organizing joint functioning of multirobot teams [889]. Most of the behavior synthesizing control schemes are meaningful in learning and experiential skill acquisition. All relevant literature is surveyed in the Part II of this Report.

1.8 Novel Methods of Synthesis of Intelligent Controller

Now is a period when the views presented in subsections 1.1-1.7 are being digested by the research and engineering communities. In a large paper [46] a synthetic view is presented which essentially explicates the benefits of blending FLC, NN and GA in a joint algorithm, which is categorized as "soft computing," and plays the role of an intelligent controller.

In [47] FLC is demonstrated to be a "universal approximator". As we understand from subsection 1.2 this is another term for describing the function of fuzzyfication as a function of generalization.

Further progress can be anticipated in the area of linguistic controllers. A powerful linkage is established between representation language, robot concepts hierarchy, and the control architecture that allows mapping control situations and control modes into each other [48]. On a more practical note, the role of linguistic approach is determined for control in a battle field environment [49]. A computer engineering aspect of a similar elaboration is shown in [50].

A number of further mathematical developments gives an opportunity to close the gap between "ad hoc" build-up of intelligent controllers and the overall body of control theory. In [51] a *cautious Wiener filter* has been developed for prediction, filtering, and smoothing. Methods of robust identification are proposed in [52] for linear time varying systems. An algebraic approach for synthesizing controllers for systems with distributed parameters is outlined in [53].

1.9 Game-Theoretic Controllers

This area is an interesting example, which illustrates the potential significance of multidiciplinarity for the area of intelligent control. During the 70s there were significant advances in using principles of Game Theory for control purposes (e.g. [540]). The promise of game theory was transparent; however, the results did not advance our capabilities in research and design of control systems with sophisticated functionalities. The game theoretic approach proclaimed in [55] which was published 20 years later shows that the tools of game theory allow for an elegant reformulation of other theoretical development in control theory. The authors in this area are aware of the important avenues linked to the psychology of the game theoretic representation of supervisory control (with possible applications for planning). However, the level of multidiciplinarity required in the area of Intelligent Control doesn't have any substantial appeal to the researchers in the area, just as it didn't have any appeal 20 years ago.

1.10 Defining Intelligent Control

The following excerpts from [56-63] should be taken into consideration in our further efforts of defining Intelligent Control.

"An intelligent system has the ability to act appropriately in an uncertain environment, where an appropriate action is that which increases the probability of success is the achievement of behavioral subgoals that support the system's ultimate goal."

The following definition emphasizes that the system in question processes information, and it focuses on man-made systems and intelligent machines:

Machine intelligence is the process of analyzing, organizing and converting data into knowledge, where (machine) knowledge is defined to be the structured information acquired and applied to remove ignorance and uncertainty about a specific task pertaining to the intelligent machine."

A procedural characterization of intelligent systems is given next:

"Intelligence is a property of the system that emerges when the procedures of focusing attention, combinatorial search and generalization are applied to the input information in order to produce the output."

In view of the above, a working characterization of intelligent systems, or of (highly) intelligent (control) machines, that capture the essential characteristics present in any such systems is:

An intelligent system must be highly adaptable to significant unanticipated changes, and so learning is essential. It must exhibit a high degree of autonomy in dealing with changes. It must be able to deal with significant complexity, and this leads to certain sparse types of functional architectures such as hierarchies." [56]

From the viewpoint of control theory, intelligence might be defined as a knowledgeable 'helmsman of behavior.' Intelligence is the integration of knowledge and feedback into a sensory-interactive goal-directed control system that cam make plans, and generate effective, purposeful action directed toward achieving them.

... Intelligence can be observed to grow and evolve, through increased computational power, and through accumulation of knowledge of how to sense, decide, and act in a complex and changing world." [57]

The following properties of intelligent systems are focused upon:

"1) A desirable property of intelligent systems is that they are 'adaptive'...
2) Intelligence is an internal property of the system, not a behavior...
3) A pragmatic reason for focusing on 'intelligent' control systems is that they endow the controlled system with enhanced autonomy." [59]

The trade off between increased functionality and computational complexity is spelled out:

"Intelligence. Intelligence is a control tool (for the system at hand) that has emerged as a result of evolution. Intelligence is oriented toward complexity reduction. Intelligence allows for an increase in functionality with a reduction of computational complexity." [60]

Viewed as a control problem, the following research areas become very important for the field of intelligent control:

"• *mathematical models for intelligent control systems;*
• *systematic (or perhaps automatable) design procedures for intelligent controllers;*
• *application of techniques from nonlinear analysis;*
• *performance analysis;*
• *simulation techniques for intelligent systems (particularly, hybrid systems); and*
• *implementation issues."* [61]

Merger of abstract and descriptive tools is proclaimed to be one of the main features:

"Intelligent control provides the fusion between the mathematical and linguistic methods and algorithms applied to system and processes. It combines effectively the results of cognitive systems research, with various mathematical programming control techniques." [62]

Yet, most of these properties seem to remain just engineering dreams:
"True intelligent control — control which replicates the most critical aggregate capabilities of human intelligence — doesn't exist in any artificial system today." [63]

G. Saridis has defined the intelligent control problem as: "Intelligent Control is postulated as the mathematical problem of finding the right sequence of internal decisions and controls for a system structured according to the principle of increasing intelligence with decreasing precision such it minimizes it total entropy." In [64] he has indicated that this definition can be constructively used for a theoretical design.

Multiple sources associated with industrial applications demonstrate that the above definitions are productive for the engineering design, too [65-66].

1.11 Evolution of the Usage of the Term *Intelligent Control*

In the late 70s, K.-S. Fu and G. Saridis introduced the combination of words *Intelligent Control*. In the 80s it was brought to the wide spread practice by G. Saridis, A. Meystel, and J. Albus via the annual IEEE International Symposium on Intelligent Control and multiple workshops on Autonomous Intelligent Control Systems. Many researchers that belong to the school of *Soft Computing* established by L. Zadeh have actively contributed to the nascent science of Intelligent Control. As far as terminology is concerned the area is not stable yet. The main issues that precluded from stability are the following:

- In 1985, when the annual symposia on Intelligent Control emerged, it was proclaimed a theoretical domain, in which control theory, artificial intelligence, and operation research intersected. This immediately created several controversial issues.

- Classical control theorists, proud of the well known high intellectual level of their results could not comply with a fact that a small group of researches "usurped" the term of intelligence in their results.
- Specialists in *Artificial Intelligence* traditionally abstained from getting involved in the dynamic mathematical control issues, and felt uncomfortable with the domain of research, involved in intelligence, while being beyond their discipline. Yet, it was broadly understood that expert system based controllers, linguistic controllers, restructurable controllers containing an on-line decision-maker about restructuring, biologically inspired controllers, e. g. "eye-hand," are definitely intelligent controllers.
- Numerous specialists in *Control and Automation* tried to avoid getting involved in the issues of cognitive science, psychology, biology and ecology associated with a notion of intelligence. They preferred to have a set of constructive boundaries, e. g. intelligent control as a blend of neural networks, fuzzy systems, and genetic algorithms.
- It was clear that the terms *Intelligence* and *Intelligent* carry the main responsibility for terminological instability. However, it was impossible to eliminate them since they also carry the essence of the scientific problem that was supposed to be resolved. The focus of interest was exactly in finding the structure, the explanation of functioning, and avenues of utilization of the mechanisms of natural intelligence that have discovered and continue to be discovered in the animate nature and in human activities, and that contain many important answers of how things should be done. This means that the problem of Intelligent Control is intrinsically an interdisciplinary problem. This is why starting in 1995 NIST and IEEE, in cooperation with other agencies, have organized a series of conferences that enhance the topic of Intelligent Control to the more consistent, yet more difficult, theme Intelligent Systems.

It would be instructive to recapitulate the definitions given to the term *Intelligent Control*.

1. K.-S. Fu linked a concept of intelligent control with the following features that were traditionally out of the scope of specialists in conventional control theory: decision making, image recognition, adaptation to the uncertain media, self-organization, planning, etc. [813].

2. G. Saridis gave the definition of Intelligent Control in [372] as a statement of expected functions containing the promise that it will "replace a human mind in making decisions, planning control strategies, and learning new functions by training and performing other intelligence functions whenewhere the environment doesn't allow or doesn't justify a presence of a human operator" (p.4). Expectantly, such systems will "solve problems, identify objects, or plan a strategy for a complicated function of a system," (p. 23); will utilize "memory, learning, or multilevel decision making in response to fuzzy or qualitative comments..." (p.447) In all these excerpts the concept of *goal* was not mentioned, because *goal* is a part of more general statement, which includes intelligent control by necessity: "...control of a process employs driving the process to effectively attain a prespecified goal" [372].

3. The most popular definition belongs to J. Albus [130]: "...intelligence [is] ...an ability of a system to act appropriately in an uncertain environment, where appropriate action is that which increases the probability of success, and success is the achievement of behavioral subgoals that support the system's ultimate goal."

4. A. Meystel has put together the information about Intelligent Control in [816, 817].

5. J. Albus and A. Meystel has presented knowledge on Intelligent Control in [969, 970].

The following are observations related to the usage in the literature of the term intelligence and intelligent control during last decade.

- In 1988 K. Passino and P. Antsaklis used the term Intelligent Controller applied for adaptive control of an aircraft: "The actions of the intelligent controller, which will depend on the detected changes, the avionic systems and the pilot, are made in an intelligent manner involving on-line decision making processes" [651]. In [657] A. Meystel has determined the main features of intelligent controllers:
  —dealing with ill-posed problems, using nested models of information acquisition, estimation, identification, representation and control,
  —using nested hierarchy of control loops,
  —negotiating cost-function among the loops,
  —performing joint planning and feed-back compensation within each loop, and
  —building up nested hierarchical system of knowledge representation.
- In 1990 L. Acar and U. Osguner proposed a rational and a mathematical theory to compute parameters of the hierarchies typical for intelligent control systems [814].
- In 1991, G. K. H. Pang describes intelligent controller as a controller, which is utilized for shaping the behavior of an intelligent system. The distinct properties of this controller is to provide for the following features [652]:
  a) it should "know" what actions to take and when to perform them;
  b) it should reconcile the desirable and feasible actions;
  c) it should vary the high resolution details of control heuristics;
  d) the acquired control heuristics should be the most suitable ones and they should change dynamically;
  e) it should be capable of integrating multiple control heuristics;
  f) it should dynamically plan the strategic sequences of actions;
  g) it should be able to reason between domain and control actions. In other words, it should use at least two levels of resolution simultaneously: the level of generalized "domain actions" and the level of elementary control actions.
- In 1992 D. White and D. Sofge in their foreword to [527] wrote: "To us, 'intelligent control' should involve both *intelligence* and *control theory*. It should be based on a series attempt to understand and replicate the phenomena that we have always called 'intelligence' — i. e., the generalized, flexible and adaptive kinds of capability that we see in the human brain." In the same book K. Astrom and T. McAvoy wrote: "An intelligent control system has the ability to comprehend, reason and learn about processes, disturbances, and operating conditions."
- A paper was published on intelligent test data generation [653]. The reason for calling the system intelligent is the feature of *freedom space*, in which a branching is suggested for generating of parameters of testing.
- In their paper [678], K. Narendra and S. Mukhopadhyay called intelligent control "a system, which includes the ability to sense its environment, process the information to reduce uncertainty, plan, generate and execute control action". They admit "as more intelligent control systems are designed, it become necessary to combine adaptation, learning and pattern recognition in novel ways to make decision at various levels of abstraction."
- In 1993 H. Xu, C. Baird and D. Riordan defined "intelligent adaptive control" as the one that provides for process description in terms of mathematical models, parameter estimation algorithms, adaptive control methods, criteria and requirements for the quality of a system's

performance, and is equipped with intelligent control and decision strategies. The latter include:

a) selecting the decision parameters through the expert systems,
b) searching the optimal parameters by parameter tuning,
c) choosing the control or decision strategy from several choices,
d) using explanation facilities of the causal mechanism for user guidance, and
e) monitoring and supervising the system in an uncertain environment [654].

- R. Isermann defines intelligent system as a system with an ability "to model, reason and learn the process and its automatic functions within a given frame and to govern it toward a certain goal" [664].
- In 1995 C. W. DeSilva has published the book *Intelligent Control: Fuzzy Logic Applications* [659]. L. R. Medsker, in his book *Hybrid Intelligence Systems*, defines Hybrid Intelligent Control as a blend of several AI systems within one control system. The set of AI systems, from which the candidates for blending are taken, is defined as follows: expert systems, neural networks, genetic algorithms, fuzzy logic systems, and case-based reasoning systems.
- In 1996 a concept of intelligent forging was introduced, which is considered to be a part of the system of intelligent manufacturing [655]. "Intelligence" is understood as integration of the dynamic simulation system for anticipating future decisions. The forging process is modeled by using variable resolution and finite element modeling, and for the lower level resolution a neural network compliance control is applied.
- O. Kaynak defines "mechatronics" as "synergistic integration of mechanical engineering with electronics and intelligent computer control and the design and manufacture of products and processes" [662].
- R. Isermann explains an intelligent control system "as an on-line expert system that comprises
— multi-control functions (executive functions),
— knowledge base,
— inference mechanisms,
— communication interfaces," in which "on-line control functions are usually organized in multi-levels." [663]
- In 1997 A. Stothert and I. MacLeod described a distributed intelligent controller that uses coordination of multiple semi-autonomous agents to control a plant [656]. At both levels of resolution an extensive protocol of supplying distribution and sharing knowledge between agents is applied. The advantages of a system are determined by using both a priori and operational knowledge for control.
- In 1998 the intelligent control system for wastewater treatment plants was created. In describing this plant the intelligent controller was defined as a system that "human-like tasks in environments of uncertainty and vagueness with minimal interaction with human operators" [658]. The authors recognize at least two levels of resolution and corresponding behavior in the systems to be controlled: the microscopic and macroscopic ones. They wrote that in intelligent control "there is a clear demarcation between the knowledge and the information about the process data and the inference mechanism for applying this knowledge. As a consequence deep knowledge of the process dynamics, i. e. the microscopic behavior of the process, is not essential. Intelligent control is therefore particularly attractive when the expertise to control a process is available in a form of linguistic rules acquired from normal operational experience." [658]

- A system for intelligent tool wear estimation was described in [661]. The system synthesizes the neural network for learning and a fuzzy mechanism for sensor fusion and modeling. In [815] an Autonomous Intelligent Cruise Control system is described where the function of intelligence is to insure equal distance from the other vehicles of platoon and compensate for the actuator delays.

I.2 The Toolbox of Intelligent Control Domain

In Section I.1, we discovered that all systems falling into the category of "intelligent controllers" are associated with an operation of moving information from one level of resolution to another depending on where the rules of control law reside. (Each control law can be represented by a set of rules). Apparently this leads to the existence of at least two levels of resolution required for functioning, while by recursive expansion of this principle the number of levels of resolution might be increased. This phenomenon of having more than one level of resolution is typical for all fuzzy controllers, neural controllers, neuro-fuzzy controllers, hybrid controllers, and expert controllers. Even behavior-based controllers that focus upon blending elementary behaviors at a single level of resolution need other levels of resolution for the overall planing.

In this section the focus is upon formal tools which are required to provide for all of these features that are characteristic for intelligent controllers. Most of these tools are closely associated with various features of multiresolutional intelligence and frequently require specific software solutions.

2.1 Automata as a Generalized Model for Analysis

It is well known that each dynamic system can be represented both by a system of differential equations or by using automata formalism [67-69]. Therefore, using the automata formalism does not testify for being within the domain of logical control as opposed to continuous representation; it carries only a meaning of using a discretized model for representing a possibly continuous system, and should be done anyway if computer control is presumed.

The use of automata models for continuous systems is a fact of engineering reality, and it turns out to be convenient for the case of stochastic systems [70], AI Systems [71], and Fuzzy Controllers as well [72]. Methods of re-computing continuous systems into fuzzy systems and vice versa are considered in [940].

The area quickly acquired fundamental mathematical results [73], and can be considered as theoretical roots for the other subdomains of control theory [74, 75].

It should be emphasized that within the very theoretical tissue of the automata theory the possibility and the need is ingrained of introducing multiresolutional automata. Such automata are based upon multiresolutional system of corresponding languages. This was clear as early as in the 1970s [134].

2.2 Resolution, Scale, Granulation: Methods of Interval Mathematics

However, all works in automata are traditionally presented in single resolution formalism. As we noticed, the phenomenon of moving information from one resolution to another plays a fundamental role in intelligent control.

There are many ways of talking about resolution. Sometimes, it defines the accuracy of representation by the value of the smallest measurable interval (distinguishability zone). In many cases, this zone is considered to be a half of the smallest division on the scale used for measuring a particular coordinate. In this particular case, it is associated with the value of error. It is understandable that because of this fact, instead of talking about levels of resolution, people are used to talking about levels of scale. It is interesting that in addition to the existing works on multiresolutional decomposition [76, 77], there is a stream of literature on scale decomposition and scale transform [78, 79].

In computer science literature, instead of talking about resolution and/or scale, researchers talk frequently about fine-granulation and coarse-granulation. The term *granulation* is used to determine the smallest zone of distinguishability, and in the area of image processing is called a *pixel* for 2-D spaces, and *voxel* for 3-D spaces. The phenomenon of granulation serves as a key concept in the fundamentals of fuzzy set theory [80], and a novel wing of mathematics. Interval mathematics focuses on all these issues [81-82].

Most of the papers in this subdomain are related to theoretical refinement of the spatial [83] and temporal [84] artifacts of the interval logic determining granulation of a level. Insightful observations are made within an area of tolerance analysis in an industrial practice of measurement [85].

2.3 Grouping: Classification, Clustering, Aggregation

Moving information from a higher resolution to a lower level of resolution requires grouping of this information, which is performed by the virtue of forming sets out of single objects and considering these sets as objects of the lower level of resolution. When the sets are formed taking into account only particular features of the objects, the process is called classification. When all or most of the features are taken into account but the number of dimensions is reduced by grouping them too, the process is called clustering. When the grouping is done not by the virtue of similarity but by the virtue of complementarity, the process is called aggregation. During the last twenty years all these kindred processes have been actively studied.

There is a place for mathematical discoveries related to the possible theory of types foreseen by B. Russell [86]. The process of clustering is considered a part of the process of fuzzyfication [87-88]. Clustering presumes dealing with the contextual knowledge [89] and requires using fine algorithmic subtleties [90]. Reduction of a number of coordinates is performed by selecting the influential data among the totality of information [91]. The amount of literature on clustering is formidable. A computer-oriented view upon the domain of clustering gives a concise representation of this area [665].

Classification is a less demanding procedure than clustering since it doesn't create new objects for the lower level of resolution; rather, it bundles together the multiple high resolution features

in order to create a single feature of low resolution. Numerous computational algorithms could be considered as alternatives to neural networks algorithms when the supervised classification is performed [92]. The rules of special classification can be formulated in the terms of fuzzy membership models [93]. The use of "commonsense" algorithms of ordered weighted averaging is very frequent[94]. The use of fuzzy techniques for computer grading of fish products is demonstrated in [98]. Nevertheless, using the standard Bayesian classification is justified with Gaussian processes [95].

There is no limit to proposing and applying new algorithms of classification. An entropy-based approach is proposed in [96]. Classification for smoothing without shrinkage is described in [97]. A hierarchical classifier for implementing an autonomous agent is described in [99]. In this robot, actions are classified within the framework of joint functioning of planning and reactive modules of control.

After clustering and/or classification is performed, the generalized parameters of a cluster or a class should be found. An example of averaging for the purpose of classification is described in [878]. A traditional approach for finding the generalized parameter or parameters is "uniformization" of properties of averaging or weighted averaging [666]. An example of averaging for uniformization can be found in [878] where the texture is classified by using averaging of the numerical evaluation for the local pattern of the texture. The most important parameter for distinguishing one averaged uniformed patch from another is the value of the threshold [879]. The "uniformization" can be performed as a cooperative grouping in a multiscale setting [667]. The efficiency of averaging approach is described in [668].

Averaging, as a characterization of the degree of uniformity for groups of information units, is a general tool for evaluating the complexity of computations [880].

Fuzzy set theory is a powerful mechanism for clustering. A further development of the clustering capabilities as applied to tables, databases, and knowledge representation systems is presented in the rough set theory [669, 670]. Rough sets are useful for knowledge acquisition under uncertainty [680].

The process of constructing "chunks" conducted in SOAR [671] is one of the practical examples of clustering [672].

2.4 Focusing Attention

Focusing Attention (FA) is an operation which is utilized the most in all kinds of control systems and reflected in literature the least, especially in the area of intelligent control. It is linked with the fact that focusing attention doesn't allow for consistent formalization. FA is rather a result of our preferences, which determine the rough division of all available information into two classes: one that contains information to be taken into account, and one that contains information to be neglected. Clearly it requires general thresholding performed upon all available information. The statistical methods like the one described in [100] are most applicable and are recommended for choosing the sampling strategy.

Methods of scoping (determining what is within the scope of user's interest) always require a participation of a human, or an introduction of a protocol, which assigns the scope in a compulsory way (see, for example, [101]). Some attention was paid in the literature to the family of methods of "windowing": information is to be taken from a sliding window where the width and the speed of sliding are prescribed based upon considerations of efficiency and accuracy [102-106].

The word window in the area of computer vision is understood as related to physical space. However, the general windowing presumes scoping the information in the arbitrary multidimensional space like weighted Parzen window [679].

Methods of focusing attention play an important role for increasing productivity of search algorithms. Finding a limited domain for the subsequent search is called enveloping.

2.5 Combinatorial Search

Any *search* is a *combinatorial search* (CS) since formation of combinations is always presumed. Methods of search are presently well known due to the efforts of professionals in computer science. Twenty years ago, the term "searching" meant browsing, and different schedules of browsing could be improved by using the techniques of operation research. Many methods of search emerged as a result of planning problems formulated as searching for the minimum cost path on the graph. Pretty soon, it became clear that only exhaustive search is to be trusted, and algorithms such as Dijkstra algorithm became a part of each programmer's toolkit.

Control people were exposed to the idea of search at a comparatively late time and were reluctant to adopt it. Dynamic programming was never welcome within the classical control community because of a horrendous computational complexity of almost all algorithms of dynamic programming. AI people found a witty tool of complexity reduction called A*-search [107]. Its area of application is limited though, because its convergence can be proven only for linear situations.

In the meantime, exhaustive search was used for planning in so-called configuration space [108]. In 1986 it was demonstrated that substantial complexity reduction could be achieved when the search is applied in a multiresolutional fashion [109]. In 1987 the same concept was proposed in the AI community [110] without reference to the original paper [109]. During the subsequent ten years, the concept of multiresolutional combinatorial search (CS) was confirmed in multiple applications. In 1996 the same concept was proposed again in [111] for neuro-fuzzy paradigm, and in [112] by machine learning community.

As a result of using exhaustive search for solving dynamic problems, especially in the multiresolutional space, the utilization of search algorithms has substantially grown. An apprehension for using it in problems with dynamics has diminished. Curtailing the space of search by using envelopes became a standard practice (so, both the SEARCH and the. In [113] focusing attention is used to modify and improve the A* algorithm (the authors call it D*).

Different methods of enveloping (FA) are explored in a variety of search (CS) algorithms. In [114] a bounded look-ahead search is discussed. Actually, this is joint use of search with

focusing attention (CS+FA). Other methods of merging focusing attention (FA) with search (CS) are also explored [115].

Another method of increasing efficiency of the algorithm of search is bounding the process of successor generation. The exhaustive search and its curtailed relatives like A* and D* tend to increase efficiency by limiting the space of search. But within the limited space they explore all possible successors. The algorithms of evolutionary programming (EP) and genetic algorithms (GA) do not explore all possible successors, they try to affect the process of successor generation [116, 117].

Finally, the search processes can be improved by further exploration of methods of computing the cost, e.g. in [917]. We would expect that this area has unlimited capabilities of further development which can be seen from numerous mathematical explorations, e. g. [118, 119]. All references from this subsection consider search for particular types of combinations — strings. There are many problems of processing intelligent controllers that are oriented towards different types of combinations. For example, in many cases of clustering we are interested in obtaining different topological formations. Instead of strings we often try to receive balls, rectangles, stars, and trees. Clustering most frequently alludes to the formation of balls. Depending on the algorithm of searching for a cluster we might end up with balls of different size, and in different zones of the space. Computer algorithms and architectural issues of combinatorial search are discussed in [673].

Tabu search [877] is a local search technique aimed at improving a feasible solution to a combinatorial optimization problem as introduced in [878]. The search begins with an initial feasible solution, a move is defined to be a modification of a given solution to obtain another feasible solution. The set of all solutions that can be obtained from a particular feasible solution by a single move is called a neighborhood of this feasible solution. The move is chosen to provide the best objective function value of all neighboring solutions. Each neighborhood has the tabu list, which is comprised of moves that are not allowed to be made at the present situation. The strategic evaluator updates the list.

2.6 Generalization

Joint application of *grouping* (Subsection 2.3), *focusing attention* (Subsection 2.4) and *combinatorial search* (Subsection 2.5) amounts to *generalization*. The latter term is not very well defined, but this is a process which allows for describing the system at a lower resolution with a larger scope, with a smaller number of details, and with the consequences penetrating further into the future. Each lower resolution level of RCS is the result of generalization of information represented at the higher resolution level. Naturally, the very fact of existence of *Generalization* (G) invokes a possibility of an inverse procedure (G^{-1}), which is called *instantiation*. Unlike Generalization that requires Search among different alternatives for a subset that should be grouped together, the instantiation executes the procedure of search among different alternatives, looking for the one that should be considered the best representation of the generalized object under concrete circumstances.

One of the traditional types of generalization, well accepted in the research practice, is approximation. Methods of averaging for receiving the simplest approximation and using

standard series decomposition are well known. Less known are randomized local approximations [120], or adaptive averaging [121], which are instrumental for modeling the unmodelled dynamics. The usefulness of fuzzy piecewise approximators has been shown in [122]. It looks like any generalizing (approximating) system should be fuzzy [123]. Generalization as a search for the fuzzy attractor is illustrated in [124]. A complete theory of fuzzy approximation for SISO case is given in [47 and 125].

Operation of generalization produces new objects. The latter belongs to the level of lower resolution that contains smaller number of entities and thus allows for computational complexity reduction. The results of generalization have always a lower resolution and lower accuracy than each of the generalized objects. On the contrary, the results of instantiation frequently produce more than one object, and the produced objects have higher resolution and accuracy than the object to which the operation of instantiation was applied.

2.7 Computational Complexity

We have already noticed that many tools under discussion either focus upon or relate to a problem of computational complexity reduction. Computational complexity is understood as an estimate for the number of elementary computations required for solving the control problem. This type of complexity is called Kolmogorov's complexity [873]. Both Shannon's and Kolmogorov's complexities serve the same purpose: to evaluate the computational complexity by judging the results of state space tessellation.

Computational complexity and structural complexity are interrelated and a designer should maintain a very intimate balance between them. In [874] this interrelation is analyzed, and it was concluded that there are combinations of an algorithmic solution and an architectural solution for information representation, which minimize the number of computations. Another measure of complexity takes into account not only the number of information units in the message but also the syntax of the message [875]. According to Chaitin's theory, the complexity of a sequence of symbols (relative to some automaton) is defined to be the length of the shortest binary program, such that when it is used to instruct this automaton, it produces that very sequence. A technique was proposed in [876] that can be used for evaluating the joint complexity for a set of information units that are syntactically interrelated.

This interest in complexity is not purely an academic one. It is driven by practical problems that very easily can become intractable if one doesn't take special measures to properly organize the processes of computation [903], in order to minimize the value of complexity. Planning robot motion in an uncertain environment is linked with highly complex computations [904]. The need for searching, like in dynamic programming, led to an increase in complexity as shown in [905], and the simple measures to reduce the complexity of the search did not give too much relief [906]. A variety of methods of complexity reduction are proposed regularly, especially in the area of control [907]. In [908] it was demonstrated that the most powerful tool of complexity reduction is organizing a controller in a multiresolutional architecture. We will describe later that construction of a fuzzy logic amounts to introduction of a multiresolutional system. The linkage extends to similar results in complexity reduction as described in [932].

It was demonstrated both in [107] and [109] that by using a multiresolutional controller, or a planning system with multiple levels of abstraction, computational complexity can be drastically reduced. Further theoretical works refine the initial findings and should be studied to obtain numerical recommendations in particular cases. In [126] the quasi-linear time complexity theory is proposed. Some of the linear time algorithms are proposed in [127] for memory hierarchies. Theoretical analysis of these algorithms is given in [128]. Some practical methods of reducing complexity in the algorithms of navigation are given in [129].

2.8 Elementary Loop of Functioning

It is imperative to remember that levels of resolution do not exist by themselves. Each of them should be considered as a part of the close loop. The closed loop control at each level of resolution is called an elementary loop of functioning (ELF). It contains six or seven modules as shown in Figure 2.8.1 [130, 131].

Clearly, the control process in ELF depends on the level of resolution for which this ELF is constructed. All examples from the literature that describe intelligent control systems use ELFs for representing a closed loop of functioning. We refer here to two examples [132 and 133].

2.9 Multiresolutional (Multiscale, Multigranular) Approach

Multiresolutional world representation was possible due to the development of the automata theory [134]. From this point of view, the emergence of the theory of fractals was not the revelation presented in [135]. It was rather premonished by a decade of active research in hierarchies of languages and automata as applied to biology (see survey in [136]).

Multiresolutional methods of world representation were quickly incorporated by researchers in computer vision and image processing [137-139]. Similar research was conducted in the area of finite element algorithms [140]. The effort in finite elements evolved into the broad domain of multigrid algorithms [141-142]. A development of all these efforts was embodied in a multiplicity of works and multiresolutional signal processing and wavelet theory [143-145].

Further developments included emergence of the multilayer logic for knowledge representation [146], probabilistic and robust methods of image segmentation [147, 148], and wavelet based techniques for pattern recognition [149]. An interesting problem emerged: whether the level of resolution should be fixed or the granularity should changed depending on circumstances [150]. Different scales or different resolutions have arrived to the area of control much earlier than the concept of multiresolutional world representation made it absolutely unavoidable. The concept of *multirate* controllers has emerged as a response to the frequent situation when bandwidth separation of control processes led to a substantial reduction of the computational complexity in control systems. Examples of multirate controllers can be found in the literature [151-154]. All RCS controllers are multirate controllers.

2.10 Dealing with Uncertainty

In many definitions of Intelligent Control, the phenomenon of *uncertainty* is mentioned. Indeed, without uncertainty the intelligence is not necessary, everything can be successfully preprogrammed. Therefore "Dealing with Uncertainty" is of key importance for our purposes. What are the methods of dealing with uncertainty employed within a domain of intelligent

control? It would be a valid question for each subdomain of the control theory. In this case, it turns out that all tools, discussed above, were actually developed for dealing with uncertainty.

The most radical tool for dealing with uncertainty is *not to describe it at all*. This means, that the controller can be built as an adaptive system, which allows for disturbance attenuation [155]. In this and similar cases, constructing the actual model of uncertainty was carefully avoided, but it became necessary to introduce the concept of unmodeled dynamics [156]. Particular models of uncertainty in some cases allow for "nice" mathematical advantages [157].

In systems with specific functions of estimation and identification, the model of uncertainty was constructed in the terms of a theory of stochastic processes. In [158] a particular case of estimation is described that employs estimation with focusing attention by a sliding window (see Subsection 2.4), which is called ARMA, and constructs the model in the terms of auto-regressive moving average [159, 160] (see Subsection 2.6).

Multiple models of stochastic approximation were used for modeling uncertainty [161, 162], and many of them alluded to using
a) averaging of the results (see Subsection 2.6);
b) separation of the stochastic sequence into different time-scale channels (see Subsection 2.9); and
c) the assumption of Gaussian statistics (the latter was overwhelming).

Yet, in numerous cases the statistics were not Gaussian at all, and methods of non-parametric statistics have been proposed [163]. In other cases of state estimation, the pseudo-linear regression was suggested [164]. All these theoretical varieties were always associated with an increase of computational complexity, and there was always a strong desire to escape these complexities by moving the problem to the lower resolution level by using a more efficient tool than the theory of probability. Fuzzy set theory turned out to be one of these tools [165-166]. An illustrative example of using fuzzy logic for uncertainty reasoning is described in [178]. The adjacent class of problems was associated with the evaluation of *possibility* [167] where the estimations don't have any statistical bases, too. The linkage between statistics and theory of fuzzy sets is presented in [168].

This blend between theory of probability and theory of fuzzy sets is called *fuzzy uncertainty*, and is instrumental in both feedback control [169], computer vision [170], and other subsystems of intelligent controllers.

Substantial attention in the literature is allocated with elements of the theory related to conditional probability in cases when statistics are not known or not available. This tool is related to the theory of belief and used for hypothesis evaluation when the evidence is uncertain [171]. A special case of belief evaluation is related to a case when we deal with multilevel preferences, which are typical for RCS value judgement [172]. More complex cases of belief evaluation are related to representing degrees of belief for objects or events organized into networks [173]. Updating procedures for the value of belief are described in [174]. These belief networks are especially instrumental for determining strings of cause-effects [175].

Recently, a novel approach to estimation can be found in the literature: when not only the model of uncertainty should be built, but also a pattern within a set of multiple sources of uncertainties should be found [176]. Further developments focused both on instantaneous patterns (patterns existing at a particular moment of time) and on temporal behavior of the sources of uncertainty, which determine the evolution in time of these patterns. Taking into account these factors would allow to plan measures how to deal with the sources of uncertainty [177].

In conclusion of this subsection, it would be prudent to notice that all uncertainty issues typically boil down to a need for using models with discrete variables. Indeed, any uncertainty is equivalent to the error in a particular variable of interest. Any error is practically a discontinuity of a representation, i. e. the information of a particular variable is discretized; it demonstrates gaps in its continuity. This discretization of information about variables can be modeled by a special function specifying the discretization of space [179]. Another evidence is the multiplicity of examples that use a tree representation [180] of uncertainty. It is possible to show that eventually, it ascends to the wavelet model (see Subsection 2.9).

Recently, a great interest has emerged in the issue of higher order uncertainty, i. e. the uncertainty in the techniques and results of evaluating uncertainty [681]. Researchers are studying second order distributions and the subtleties of acquiring these distributions [682]. It turns out that in the serious cases the higher-order uncertainty might be of key importance for each decision maker or a decision making subsystem [683].

2.11 Reasoning

All tools applied in intelligent control systems and described in the subsections 2.1-2.10 are tools of reasoning[1]. The Theory of Automata suggests how to reason about systems that transform an input string of symbols into an output string of symbols if the transition and output functions are given as mappings of these symbols into each other. Organizing information in multiple levels of resolution is a mechanism of reasoning about objects that can be represented with different accuracy.

Grouping is reasoning about unifying a set of components into a single object. *Focusing attention* is reasoning about information streams: which part of it can be neglected. *Combinatorial Search* is a reasoning of finding the best string or the best cluster. *Generalization* is reasoning about forming new levels of abstraction. Reasoning of temporal processes with closure requires introduction of the elementary loops of functioning. Organizing overall information into a multigranular system is reasoning about how to reduce complexity of decision making. Creation of probabilistic, possibilistic, and fuzzy models is a set of different ways of reasoning about uncertainty.

Why have a separate section on reasoning? That can be explained as follows. Reasoning is required for obtaining implications. These are traditionally associated with "deduction." Yet, "induction," "abduction," and other tools of plausible inference produce implications as well. It would be useful to find common laws of reasoning for all the above cases of reasoning. The

[1] Reasoning – 1. to use the faculty of reason so as to arrive at conclusions; 2. to discover, formulate, or conclude by the use of reason (Merriam-Webster).

expectation of the existence of such common laws is looming. These are two major premises that support these expectations.

The first premise of reasoning: the practice of dealing with systems is a practice of organizing information into classes, and gradually constructing hierarchies of these classes, so that the collected information could be found and used. Thus, the laws of organization of information should be declared that would allow reasoning about membership in particular classes.

The second premise of reasoning: the experience of dealing with information demonstrates that all cause-effect inferences that are of utmost interest to the user cannot be obtained solely from past experience. Some of them should be anticipated. There is a hope that because of epistemological redundancy, ingrained into stored information, the inferences of interest are hidden in the previously stored classification and multiple cause-effect statements. The role of reasoning is to infer the required cause-effect statements from the already existing ones.

These two premises explain the aspects of further discussion. The development of inferences and obtaining implications is required for normal functioning of the intelligent controller. First, these could be simple tautological inferences that allow for the theorem proving and do not necessarily deliver any novel information. Second, the tools of reasoning must be found that necessarily lead us to the non-trivial results.

The pragmatic part of this introduction can be formulated as follows: all available knowledge of the world is represented in two databases: the one with multiple hierarchies of objects belonging to classes (DB-1), and the second with multiple hierarchies of cause-effect statements (DB-2). The goal of reasoning by using these two databases is to receive either images of the objects we lack in DB-1, or statements of cause-effect we lack in DB-2. The expectation is that the laws of manipulation of information exist and allow for receiving these two desired results.

General Issues

The following general issues should be taken into account while discussing the subtopic of reasoning:

a) the fact that it is impossible to provide for a consistent[2] reasoning process is one of the factors that determines the need for a multiresolutional representation: it follows from Godel's theorem of incompleteness [181];
b) difficulties in obtaining a consistent representation at a level is aggravated by the realistic situation (presented in natural language descriptions with multiple sources, sets of various sensors, maps, etc.) where the redundancies and lack of information ("don't cares") are dealt with in a disorganized manner, or even disappear in systems of representation [182];
c) specifics of reasoning in intelligent control systems can be formulated as a need of *reliable implications* based upon available representations rather than constructing the representation for satisfying a set of rules of reasoning without verifying the implications it produces [183];

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[2] Consistency – the ability to be stated (asserted) together without a contradiction (Merriam-Webster). *Consistent reasoning process* – the one that does not contain contradictions. In logic: a method for establishing the consistency of an axiomatic theory is to give a model.

d) a strong factor affecting the techniques of reasoning is practical abandoning of missing data (in addition to redundancy mentioned in "b") [184].

Therefore, the systems of reasoning should be flexible enough to incorporate
—quantitative as well as qualitative reasoning,
—generation of limited suggestions, as well as temporal reasoning,
—construction of indirect chaining tautologies as well as constructing direct inference [185],
—employing non-monotonic as well as monotonic reasoning,
—deriving implication from direct experiences as well as reasoning by analogy, and
—utilizing both certain as well as plausible reasoning.

All possible advances in developing these kinds of reasoning should be supported by processes of comparison and selection and materialized in software packages. Examples of reasoning that use many of these tools simultaneously are described in [19, 186 and 187]. On the other hand in most systems there are several parallel processes of reasoning, and their results should be integrated [685]. The latter problem invokes the need for searching for consensus [686].

The initial and final issue of any reasoning process can determine the validity of the overall reasoning. Indeed, before we start dealing with chaining the rules, these rules have to be learned from databases [684].

Qualitative Reasoning

Qualitative Reasoning is a theory of dealing with the weakest possible statements of class-belonging and cause-effect that have been obtained from qualitative observation. Although, this type of reasoning is very reliable, it is often insufficient for multifactor on-line decision making. Its general maxims are presented in [188]. A generation of layered causal models is presented in [189] for failure analysis. An example of reasoning about motion is given in [190].

Some theoretical advancements in this area are related to further development of belief models [191] and to theoretical models hypothesis generation in their temporal analysis [192].

Theorem Proving

Most of the problems emerging in Intelligent Control may be formulated in terms of theorem proving if the latter will be understood as a creative process including the element of discovery. However, a history of theorem proving demonstrates a strong orientation toward just construction of the tautology chains like in a well-known AI case of resolution-refutation. A history of automation of proof is described in [193]. The orientation toward construction of the chains of tautology can be applied even under uncertainty [194], and in the cases of multistrategy situations, for example, using knowledge-bases [195].

Classical schemes with resolution-refutation can be applied in parallel inference machines [196]. Practical applications are very broad. An example related to proving safety is given in [197].

Temporal Reasoning

From the very beginning of using logical schemes for control systems based upon automata models, it was clear that the significance of the temporal transition models couldn't be

overestimated [198]. For the purposes of control theory it meant finding the temporal behavior of automata, e.g., within supervisory schemes [199]. Within the AI paradigm, this was done by using the logic of actions [200], where cause-effect relations require making statements about frames, bounded by our focus of attention.

Temporal reasoning should be practiced for all problem of planning under uncertainty [201]. A very short term planning boiled down to the property of reactivity which is often associated with particular time constraint [202]. All event-based processes alluded to temporal logic, sometimes with uncertainty factors, sometimes in the paradigm of fuzzy theory [203]. In both cases the use of knowledge.bases was presumed [204].

Temporal logic allows for integration with normal inference rules [205]. An example of using temporal reasoning for diagnostics is given in [206]. Within architectures like RCS, concurrent functioning of event-based controller at a level is a regular operation. The fundamental analysis of related concurrency issues can be found in [207].

Nonmonotonic Reasoning

The problem of nonmonotonic reasoning emerges in all cases related to dealing with semantic networks, natural language representation, where epistemic logic is needed [208]. The regular algebraic theory of computational languages doesn't suffice [209], since it doesn't address the issues of belonging to a particular context. This issue is not addressed in classical AI presentation either [210]. An important issue of relations between the logical statement and its context is the issue of belonging to a more general representation of a situation, in other words, to the lower level of resolution. This evokes the need to understand processes of generalization and clustering [211, 212].

Technically, the nonmonotonic reasoning constructs a scale of truth where different values of truth are characterized by different values of confidence in different contexts [213]. Measures of confidence are not necessarily based on human expertise; the value of "confidence" can be evaluated by using well-defined analytical expressions from computed variables, or experimental data. Some results in nonmonotonic reasoning are oriented toward measuring the entropy of statements of interest [214]. There is a linkage between nonmonotonic reasoning and the ordering of statements by the values of their possibility [215].

Probabilistic Inference

We have already mentioned that probabilistic reasoning is one of the frequent schemes of evaluating the reliability of logical statements. This evaluation is based upon qualitative "event generators". The recommended inferences are determined by the relative frequency of events that can be generated by our quantitative model. In [216] a model of probabilistic reasoning is presented for evaluating the condition of a car, which leads to a hierarchical decision tree in which probabilistic inference is possible. An effort to blend the probabilistic event generator with predictive models in which the size of sample is the variable is given in [217].

Possibilistic Inference

This type of inference employs the apparatus of First Order Logic typical for probabilistic models to which corrections are introduced by L. Zadeh, D. Dubois and H. Prade [218]. There is

a substantial overlap between the results on semantics of nonmonotonic reasoning and semantics of possibilistic reasoning [219].

Analogical Inference

Analogical Reasoning is a precursor to any inductive reasoning when we arrive at a conclusion by finding a similarity or analogy between evolving prior results. Analogical arguments are discussed in [220]. The analogy always presumes that there exists some structural similarity between the observed systems and its representation, or between several systems of representation. An effort to demonstrate how the analogical similarity can be used in practice is reported in [221, 222].

Plausible Reasoning: Abduction, Evidential Reasoning

All methods of plausible reasoning allude to insufficient information. V. K. Finn has developed a persuasive mathematical analysis, which shows that there are cases when the validity of reasoning under conditions of insufficiency of information can be proven mathematically [223]. The author uses the model of reasoning that was first introduced by J. S. Mill and calls it JSM-Reasoning. In [224] it was demonstrated that some methods of JSM-Reasoning ascend to multivalued logic.

An approximate reasoning based upon using fuzzy logic is described in [225]. There exists an abundance of methods of reasoning which are called ***abduction*** and are actually reasoning by ***induction with insufficient statistics***. In most of these cases the justification for abduction is found in some circumstantial evidence taken from probabilistic semantics networks or possibilistic networks [226]. There are even some software packages based upon this approach [227]. Abduction is known to be successful in diagnostics [228, 229]. There are papers that try to develop a theory of circumstantial evidence to justify abduction [230]. A model for evaluation of circumstantial evidence is described in [687]. A mathematical approach for evaluating a composite evidence (an evidence that is combined from a variety of sources) can be found in [688]. Abductive reasoning is compatible with probabilistic temporal prediction [231]. Most of the computational approaches for all of these methods are discussed in [232].

Neural, Fuzzy, and Neuro-Fuzzy Inferences

All these method of reasoning found broad application in fuzzy logic controllers, usually including neural network components. National Semiconductor's NeuFuz system combines fuzzy logic and neural networks which learn a system's behavior and generate fuzzy rules. The system is equipped with a fuzzy rules verifier that validates generated rules and optimizes their numbers [233]. Systems of this type are abundant in the contemporary industrial practice. Theoretical explanation for the processes of these type of systems can be found in [234]. The mechanism of constructing a network of neuro-fuzzy inference is described in [235]. The degree of resolution of fuzzy logic inference can be evaluated by using theoretical premises [236].

The ways of fuzzyfication and de-fuzzyfication affect the resulting rules at both levels of resolution involved in transformation. The legacy influence is demonstrated in [689]. In some cases, it is possible to avoid taking into account the legacy influence and use similarity based fuzzy reasoning methods [690].

2.12 Comparison and Selection

Usually, all methods described in the previous subsections are applied to prepare the alternatives for the future solutions, and a *Selector* should exist that makes a final decision on the preferable choice. Any procedure of clustering requires choosing a preferable cluster. Within a procedure of clustering at every step we should make a choice: into which available cluster a particular object should be included. The simple model of selection is based upon comparison using a particular distance measure [237]. Different techniques should be used depending on configuration of decision regions, whether they are convex or non-convex [238].

The process of selection can be substantially complicated if the alternatives should be searched for, and in the same time there is more than one criterion for comparison of these alternatives [239]. Even more complicated is the process of selection when we have a combination of multiple criteria and multiple decision makers that are competing with each other [240]. Even if decision makers cooperate, the problem of voting is what selection frequently boils down to [241]. In all of these cases the phenomenon of "regret" is supposed to be taken into account [242]. Methods of gain theory allow resolving some of the conflicts that emerge in the cases with the multiple decision makers [243].

One of the working tools of the selection process is a procedure of matching. The theory of matching multiple patterns is presented in [244]. More complicated cases of matching are typical for systems of computer vision [245]. In all cases of matching, we deal with hierarchies of features, selections and discriminations [246]. Matching can be a time consuming operation and affects the complexity of an intelligent controller [247]. Matching is frequently associated with threshold selection, and relies upon probabilistic methods [248].

Critical cases of comparison and selection are associated with solving the control problem of identification [249]. This problem is similar to the problem of model construction [250]. Another domain of application is conflicts resolution [251].

The early problems of AI led to the need for comparing problem solving methods [252], while at the present time multilevel decision making is a problem for novel control architectures [166]. It may happen that the Selectors of different levels of resolution should be connected to each other in assigning the strategy of selection.

2.13 Software

All methods of reasoning rely heavily on software packages. Optimizing software for reasoning sometimes gives substantial financial reward [254]. Most of the available sources of improvement are hidden in the subtleties of object-oriented databases and interaction between elements of a program, or a user and a program [255]. This area is very active: there is a substantial information flow, many conferences, and research departments in various organizations. However, it is not rich theoretically; at least, no independent theoretical framework has been declared; also there are papers that are engaged in establishing a theoretical background for the software improvement [256].

I.3 Sensory Processing

In Sub-section 2.8, the ELF was introduced as the building block of any Intelligent Controller. ELF consists of the following subsystems: Sensory Processing (SP), World Model (WM), Behavior Generation (BG), Actuators (A) and Sensors (S). All external information is delivered into the subsystem of Sensory Processing (SP). In the same way as the whole intelligent system consists of SP-WM-BG which submits control sequences to the system of actuators, the system SP of sensory processing by itself can be also represented by a block diagram with its own input processing faculties, its own knowledge representation, and its own behavior generation, which provides for planning and execution only sensory processing activities. Naturally, as the overall intelligent control system precipitates into a multiresolutional architecture, which minimizes its complexity, the subsystem of sensory processing can be organized into its own multiresolutional system, which minimizes the complexity of its own sensory processing. The levels of resolution of SP, as we will see, do not necessarily coincide with the levels of resolution of overall intelligent controller. Sensory processing is a self-contained area of scientific, engineering and psychological endeavor, which has developed its own languages (e. g. as in [257]), its own methods, like space scale representation [258], and its own ways of dealing with hardware [259].

In this section we will address only the specifics of sensory processing that are related to intelligent controllers.

3.1 General Issues

A fundamental question explicated or tacitly presumed in all papers on sensory processing is the issue of the coordinate transformation which eventually maps sensory inputs to realistic or virtual actuator outputs. In [260] authors argue that "visual inputs are collected in the coordinate frame of the retina on which the visual environment is imaged, but motor movements such as reaching are made to locations in external space. Changes in the eye position will alter the retinal locations of targets while their spatial locations remain constant. As a result, visual inputs must be transformed from retinal coordinates to coordinates that specify the location of visual objects with respect to the body to perform accurately directed movements."

Other transformations can be introduced depending on the system at hand. Indeed, in a mobile autonomous robot, a system of computational transformations is required between ego-sphere coordinates and global coordinates [130]. Among other fundamental general issues the following should be mentioned:

a). Multiresolutional representation which should minimize SP-related computations.
Among the recommended methods the most significant are methods of quadtrees [261] and multigrid relaxation method [262]. Similar multiresolutional representation is the hierarchical scene labeling [263].
b). Construction of the fundamental model of sensory representation.

There is no agreement on the preferable form of models. For the case of vision, useful models are proposed in [264]. These models are supposed to reconcile different visual laws that are conflicting in some details. In [265] a comparison is conducted of various models by the method

of simulation. These models are used for both direct and inverse mappings [266]. Models applicable for motion estimation are discussed in [267]. Inverse kinematics of multi-link manipulators are analyzed in [581].

3.2 Depth and Range

A problem of determining depth and range with sufficient accuracy is of special importance for SP and intelligent controllers because of uncertainty, which is associated with these measures. Using radar and laser range finders doesn't eliminate this problem; it just moves it into a different framework [268]. Binocular stereo methodologies frequently rely upon "sepstral" filtering [269], which uses frequency analysis of some algebraic transformations of numerical data. Methods of comparison for stereo images are presented in [270]. The method of focal gradient for estimated distance is described in [271].

3.3 Image Processing

The difference between the 90s and the 80s in the content of the weakly organized toolbox of Image Processing is in the fact that algorithms became multiresolutional while the techniques remained the same as before. In the 80s the methods of detecting edges were precisely formulated (e. g. [272]). This problem is not out of fashion even now [930]. The multiresolutional technique for edge detection was called a pyramid [273]. In the 90s, the multiresolutional algorithm of image processing turned out to be regular practice [274, 275]. The multiresolutional method of quadtree information organization (and later – octree) became frequent for solving problem of image compression [276].

It became a common practice not to use any analytical forms for encoding spatial relations. The neural networks for learning complementary relations turned out to be more flexible than stiff analytical constructions [277]. Level of resolution is now considered to be a factor determining sampling of images which turned out to be important in a model-based vision [278], and in various systems of image segmentation as well [279]. More attention is paid to methods of segmentation when occlusion is expected [280], which often allows for obstacle detection by using indirect information [281]. All of this allows for development of new tools of feature extraction [282].

Various methods of filtering have been introduced including adaptive structures, efficient in a broad range of probabilistic conditions [283]. Nonlinear methods of filtering have been applied successfully for enhancement of edges and corners [284]. Integration of image modules was equipped with novel mathematical methods, which used the concept of fixed zones of attention. The example with Ames trapezoid window is described in [285]. Sliding window based tracking of roads and intersections is described in [286].

3.4 Image Interpretation and Understanding

The general approach to image analysis including interpretation and understanding does not deviate from the joint use of syntactic and statistical methods of pattern recognition outlined by K. S. Fu [287]. R. Haralick's methods of mathematical morphology are a good complement to syntactical models [288]. Elements of the image are frequently identified by using autoregressive models [289]. There are not too many innovations in the overall systems for interpretation and understanding. All of them employed standard syntactic methodologies [290], which, in the less

structured cases, evolve into more general rule-based systems [291]. The issue is surveyed in depth in Part II, Section 10.

3.5 Motion Analysis

Motion Analysis can provide many powerful clues for image interpretation while creating additional problems because of blurring and perceptual instability. Neurocognitive views on motion analysis provide interesting hints suggesting how to deal with this problem in a computer based system [292]: "The cortical representations of moving images may be transformed from absolute retinal coordinates into a relativistic coordinate frame using local motion information intrinsic to the retinal image." The latter is " linked to the local velocity field so that common (reference) image motion is subtracted out during visual processing." Certainly, this is a premonition of optical flow analyses and representations.

The information of motion should be supported by a thorough estimation of the absolute position [293], which sometimes allows for direct recovery of motion [294]. Interestingly enough, motion estimation and analysis leads to the multiresolutional image representation [295]. This paper [295] employs the theoretical framework of image pyramids. Later, the inner mechanism of multiresolutional motion representation is explained in [296] by using well known clustering algorithms.

Functioning of Motion Detectors is improved by prediction devices [297]. At a particular level of resolution deformable templates should be used within various spatio-temporal data models [298]. Similarly, the deformations are introduced not only to elementary units of the image but to the larger apparent contours [299].

Multiple sources of disturbances are to be taken into account in motion analysis problems. One of them is associated with the stereo transformation of ego-motion mapping [300]. Dealing with systematic errors can be learned with experience [301]. Global robustness can be achieved by methods of theory of nonlinear systems for dealing with state measurement disturbances [302]. In most of the practical problems the sources of error can be treated as multiparameter stochastic processes [303].

3.6 Concepts of Sensing

The variety of conceptual architectures is converging in the present time to a more or less uniform view of perceptual organization [304], which confirms the earlier theoretical views on the structure of images [305].

3.7 Sensor Fusion

The area of sensor fusion is still in transition. Many of the new methods turn out to be just new methods of approximation [306]. Very often, using multiple sensors requires well-organized logistical systems similar to one described in [307]. In some cases fusion is easier not at the level of sensory processing, but after SP is finished and we have to fuse multiple objects into a unified world [308]. Nevertheless, many of the sensor fusion problems can be successfully solved by using non-parametric models for blending fuzzy data [309] and methods of dealing with evaluation of relations in the graph theory [310].

3.8 Estimation

The theory of estimation based upon on well-established mathematical methods [311]. These methods are being polished in time but maintain the same theoretical core [312]. Practical applications of these methods can be found in [313]. More sophisticated applications of the same methods are demonstrated [267]. A host of experimental data is demonstrated in [314].

The advantages of recursive estimation can be demonstrated for the cases when the comparatively unknown senses are used [315, 316], or not well formalized approaches are used for object recognition and data organization [317]. For the case of vision, the techniques of recursive estimation is described in [809].

I.4 World Model

Actually, the problem of World Model is presented implicitly in all previous sections. Indeed, sensors presume a system of representation, which receives from them the information updates. Reasoning manipulates with information that either has been previously been stored in the system of representation or was initially received, reasoned with, and then, stored. It is also prepared by our prior presentation that the information will be stored in the multiresolutional form. Most of the issues of representation concentrate around multiresolutional information representation [318-320].

4.1 Multifrequency Representation

Multifrequency representation is an enhancement of an idea of the Fourier Transform, which has expanded into a window Fourier Transform or Gabor Transform, and later into Wavelet Transform. The latter decomposes the signal into a family of functions which are translations and dilations of one of the possible base functions. Also in [321] wavelets are considered to be the theoretical underpinning of the pyramid representation as in [274] or [322]. They all are just further developments of the Fourier and Gabor earlier ideas.

4.2 Quadtrees

Like the previously mentioned wavelet transform, quadtrees don't really care about multiple resolutions. Both wavelet transforms and quadtrees have the same resolution at all levels: the highest possible resolution. Using the quadtrees is just a convenient technique of hierarchical referencing the elements of representation [323, 324].

4.3 From Multiple Scales to Scale-Transform

The fact that the concept of scale is very demanding and determines the granularity of state-space was considered a secondary one in the earlier papers on multiple scales representation [325]. The attention to scales and the sense of granulation came from applications such as texture segmentation [326], top-down segmentation for object detection [327], multi-scale shape representation [328]. Thus, the problem of choosing the optimal scaling method has emerged [329]. At this moment the computer vision community started reconsidering determining resolution in the gray level image pyramids [330]. It became clear that more rigid mathematical methods should be introduced, and the "scale-transform" has emerged [331-333]. Different approaches have been used for morphological filtering with multiple scales [334]. In

[335] several time frequency representations are compared on the value of resolution that can be achieved in them.

4.4 Multiple Resolutions in Descriptive Representations

The factor of resolution was traditionally overshadowed by the issue of abstraction [336]. Also, the phenomenon of nestedness was acknowledged among the intrinsic practices of knowledge-based systems [337], and reflected in the decision tables [338]. The granularity of detail is very important when the system of constraint satisfaction is being constructed [339]. On the other hand, while specifying rules of reasoning for inconsistent knowledge bases, the attention to the level of detail turned out to be a must for overdetermined models [340]. The multiresolutional character of knowledge was raised as an issue of integrity and security of knowledge in multilevel semantic networks [341]. For taking care of these phenomena, the value of resolution should be specified for both space and time at each level of the system [342]. Methods of demonstrating multiresolutional hierarchies were proposed in [343]. The standard predicate calculus is not sufficient for reasoning in the multilevel system with multiple resolutions, and useful additions to the rules of reasoning have been proposed [344].

4.5 Implicit Acknowledgements of Multiple Resolutions

Literally, all databases and all knowledge bases have accepted the multiresolutional approach. An example of hierarchical knowledge organization is given in [345], which can serve as a source of multiple cases of using the MR concept. The robotic application of a syntactic system for decision-making [346] contains an implicit use of the multiple resolution concept. A good example of a behavioral science can be found in [347]. Actually, all sub-module inclusions in databases testify for connections between two different resolutions [348].

4.6 Multiresolutional Semantics

All cases of multiresolutional connections in databases and knowledge bases are realizations of multiresolutional semantics. In [349] a semantic method is described in which this property is mentioned. The same property is described for a relational query language in [350].

4.7 Evolution of the Automata Model

There are several developments stemming from the theory of Automata. The standard schemes have been further developed by adding the probabilistic evaluators in addition to the cost or instead of it [351]. In the same way the evaluators could be fuzzy or presented in multivalued logic. All of these are allowed by the proposed model.

Another useful development was an introduction of Petri Nets (PN) [352]. PN enhance the functionality of conventional automata schemes by making the edges of the automata graph active and controlled. It is hard to judge whether the use of PN will become more widespread. In [353] they are presented as an alternative to automata as a part of real time control architecture.

4.8 Object-Oriented Bypassing of the MR-Issues

During the last ten years, object-oriented approaches became prevalent in the area of databases and complex system design [354]. The very concept of the object-oriented system is based upon an idea of an object "equipped" by references to other objects. These objects either a) are included into the original object as its component or parts, or b) include within themselves

the original object as their component or part. The concept quickly became a substitute for the multiresolutional methodologies especially in the cases when the research or manufacturing team contained many people with computer science or software engineering background [355, 356]. The roots of the object-oriented approach can be easily detected in the earliest papers on document databases [357].

4.9 MR-Issues Related to Logic of Representation

The mechanisms of non-monotonic logic turned out to be well suited to multiresolutional knowledge representation. In [358] W.F.S. mechanism (well-founded semantics) was introduced for constructing the logical control modules. In this paper, the mechanism of intelligent branching is proposed as one of the alternatives for inverse generalization (or instantiation). The mechanism of focusing attention at a level of resolution is described in [359]. This mechanism allows dealing with hypothetical statements of exceptions to generalizations when the classical logic cannot be used. The advanced methods of temporal logic applicable to hierarchical systems of knowledge representation are described in [360 and 361].

Multiresolutional approach is tightly related to fuzzy logic approach as far as world modeling is concerned. It is not difficult to discover that construction of a fuzzy logic [931] presumes introduction of indistinguishability zones and levels of resolution.

4.10 Simulation

Taking into account the challenges of multiresolutional systems of knowledge representation is imperative when simulation is the basis for constructing the models for subsequent judgement. Some of the models are proposed in [362]. There is a definite need for symbol grounding via constantly checking the conditions of functioning at the output. This generated a need for a service that models the situation in logical (automata) terms. In turn, this created a need for finding the limits of correct judgement and developing techniques of evaluating the impact of possible errors [363]. In a variety of complex systems, the qualitative simulation which allows properly identifying and refining the model structure is applicable [364]. Similar models of simulation are constructed to verify of our knowledge in the systems that are represented by analytical equations [365-366].

The simulation systems for knowledge representation are especially important in the cases of robotics. The package Cimderella for neuro-controller design is described in [367]. The results of simulating flexible manipulators are presented in [368]. The concept for simulating robust controllers is described in [369].

I.5 Behavior Generation

Behavior Generation is the central issue in the Intelligent control area. In this section, we presume that explanations for the unclear terminology can be found in [494, 495].

5.1 Planning

The preliminary familiarization with [912] is desirable.

Brief Chronology of Evolution

Until recently planning was a domain of activities beyond the scope of a control engineer. During the last fifteen to twenty years this has rapidly developed, and has become a legitimate part of intelligent control.

Planning is an intersection of a triplet of weakly related scientific paradigms: Operation Research (OR), Artificial Intelligence (AI), and Control Theory (CT). OR emerged in the 40s and spurred the analysis of queues, graph theory and methods of optimization. As an AI extension in the 60s, the study of planning targeted corresponding processes of human cognition, and the first effort in explicit analysis of planning algorithms was related to human thought simulation [370]. A. Newell, H. A. Simon, N. Nilsson and other prominent researchers in AI have developed the fundamentals for the existing results in the area of robot motion planning. Traditionally for AI, planning was not involved in any "dynamics" which was always considered a prerogative of the Control Theory.

In Sub-section 1.10, the development of the conceptual fundamentals of Intelligent Control is demonstrated as evolution of CT toward OR via incorporation of planning and toward AI via using recognition in the loop [371, 372]. This eventually brought to fruition a new direction: Intelligent Control [373]. As a discipline, Intelligent Control blends OR, AI, and CT. It is concerned with analysis of planning, particularly for robotics. After this, the mainstream of specialists in CT realized that the so-called "reference trajectory," which is always regarded as the input to control systems, should be considered a "plan" and be computed as a part of the design process. However, the traditional control specialists considered everything related to Intelligent Control not sufficiently immersed into a rigid mathematical paradigm and therefore being extraneous for CT. The latter is related to the efforts of developing a theory of planning that started with STRIPS.

STRIPS [374, 375] and A* [376] became classical fundamentals of planning in robotics. The subsequent development in the area of robot path planning branched enormously:

a) the problems of representation turned out to be very critical
b) it became clear that both combinatorics of tasks and dynamics of systems are intertwined
c) planning processes tend to develop hierarchically in space via task decomposition and in time via search trajectories
d) the complexity of computations became the real limitation for the development of theories.

These are the milestones of the evolution in the area of motion and path planning:

- In 1966, J. E. Doran and D. Michie applied graph-theoretic mechanism for path planning [377].
- In 1968, W. E. Howden introduced the "Sofa Problem" treating the geometric problem of motion planning [378].
- In 1968, the A* algorithm was introduced by P. Hart, N. Nilsson and B. Rafael [376].
- In 1971, STRIPS was presented by R. E. Fikes, P. Hart and N. Nilsson [374,375].
- In 1979, the concept of search was attempted for dealing with obstacles by T. Lozano-Perez and M. A. Wesley [108].

- In 1979 J. Albus introduced the methodology of task decomposition for hierarchical systems; later it became a part of the RCS methodology with nested planning processes at all levels of the control hierarchy [380].
- In 1981 T. Lozano-Perez applied "configuration space" to manipulator's planning [381].
- In 1983 C.-S. Lin and P.-.R. Chang proposed a method of synthesizing the motion trajectory out of pieces of Quartic Splines [379].
- In 1983 M. Julliere, L. Marce, and H. Place outlined their mobile robot with planning via tessellated space [382]. Both methods of "configuration space" and planning via tessellated space were focused on finding the trajectory of motion in assumption that the final goal has only arrived from an upper level of a hierarchy.
- In 1984 M. Vukobratovic and M. Kircanski developed an analytical method of synthesizing the motion trajectory by using an inverse technique for the case when the number of degrees of freedom exceeded the number required for performing the operation. This planning was done with the presumption that the desirable trajectory had been assigned by somebody else (e. g. had arrived from the upper level of hierarchy of control). [383]
- In 1984, R. Chavez and A. Meystel [384] introduced a concept of searching in the space of various (non-uniform) traversability.
- In 1985, J. E. Hopcroft, D. A. Joseph, S. H. Whitesides analyzed the geometry of robotic arm movement in 2D bounded regions [385].
- In 1986, A. Meystel demonstrated that the most efficient (least computational complexity) functioning of multilevel learning/control systems with search for the planning could be provided by a proper choice of a ratio of lower level/higher level of resolution [109]. This concept of planning/control hierarchy became a strong theoretical support for the hierarchical architecture of intelligent system. The ideas of Multiresolutional Planning were discussed within the framework of Quadtrees representation [392]. However, the possibility of planning separately at multiple levels of resolution had not been contemplated before.
- In 1985-87 M. Arbib's school of control via "schemata" came up with numerous schemes of "reactive" behavior [408]. This gave birth to a multiplicity of robot control concepts, which explored and exercised reactive behavior generation.
- In 1987 the cycle of research papers related to "visibility lines planning" was practically completed. Algorithms based upon visibility lines became a standard solution [393, 394].
- Planning of optimum tracking was performed as scheduling of motion for the trajectory that was preassigned as a contour [386]. Dealing with disturbances was interpreted as a part of following preassigned trajectory [387].
- During the period 1985-1995, many researchers associated problems of robotic motion planning with short term (local) reactive behavior (like "obstacle avoidance"). Nevertheless, interest in search in the state space was perpetuating. Many examples related to this period are described in the subsequent subsections.
- Simultaneously, with many efforts to resolve the planning problem, another direction in research was gaining in popularity: to avoid planning at all. The primary focus of robotics shifted to the area of systems, which do not require any planning (robotics with "situated behavior"). Thus, the interest in planning diminished (R. Brooks, MIT, R. Arkin, Georgia Tech) and the curiosity of researchers shifted toward emerging phenomena in non-intelligent robots.
- It was typical for planning techniques introduced at this time to use potential field surrounding obstacles. This was convenient because a robot doesn't need to choose the

trajectory: it just remembers where the goal is, and the potential fields push the robot into the least resistance trajectory. In [390], Warren compares planning by using potential field with planning that employs path minimization. The observation was made that to look for minimum path trajectory might be a more efficient way of planning the path.

- In 1991, a comprehensive text was published by J.C. Latombe [388], which outlines most of the theories and experiences approved by the practice in a variety of applications. It happened a whole decade after the first textbook edited by M. Brady, J. M. Hollerbach, T. L. Johnson, T. Lozano-Perez and M. T. Mason [389].
- Ten years of research and experience (1982-1991) helped to clarify the important maxim: the process of robot motion planning can be performed efficiently only by searching within the state space and thus, determining both the final goal, and the trajectory of motion leading to this goal. At the present time, search in the state space is a prevailing general technique broadly applied for the algorithms of planning. Nevertheless, many other concepts and systems exist too, in a multiplicity of research schools and domains of application.
- In the beginning of the 90s more researchers explore planning the actuator input by inverting the prescribed output trajectory [391].
- R. Sharma and Y. Aloimonos [395] enriched the theory of configuration space by the concepts of coordination and by using permutations of the quad-tree elementary blocks. An attempt to blend configuration space with control dynamics was made in [396]. The same concept was enhanced by blending the concept of configuration space with the self-organizing distributed architecture in the system called SOBoS (Self-Organizing Body Schema). A conjecture was made that this is how cortical maps deal with the problem of planning [397]. The theoretical background for these efforts was presented [398].
- The last decade is characterized by rediscovering planning techniques that has already been documented earlier by refining them and adding to them new theoretical facets. In [399] the technology of planning via visibility lines was reconsidered. Its results confirmed most of the prior findings. In [400] an effort is made to generalize the techniques of path planning in a polygonal world by using visibility lines and/or Voronoi Diagrams. In [401] all of the prior results are enclosed in the framework of minimal geodesics theory, which ascends to Hamilton-Jacobi types of equations. Old algorithms are reviewed and important corrections are made [402]. In [403] all these planning problems are put in the paradigm applied earlier in computer vision where the methods of thinning and skeletonization are used. An effort to translate all of these problems into AI language is done in [404]. On the other hand, some advancements are made by the efforts to apply known theoretical methods by using neural networks tools [405]. Useful practical problems were resolved for the cases of positioning the robot's arm [406]. Predictive controllers are used to improve performance of the standard collision avoidance tools [407]. Predictive algorithms of planning are described in [926].
- Scientists following the Wonham-Ramatge school of control theory developed some components of the theory of planning under the title “Supervisory Control”. This theory took advantage of the convenience of automata representation, and gradually built up a level of "supervisory control" which is nothing else but the lower level of resolution in the system of representation and control. This theory developed all features characteristic of the theory of planning as formulated for discrete-event systems. Their supervisory level can have “variable lookahead” policies [409]. In this particular paper, the bounds for searching the automata behavior are assigned by the “lookahead window”. Search is demonstrated as a flexible and

easily reconfigurable set of procedures when the automaton is introduced as Petri Nets. Formulating a temporal logic makes this type of planning traceable and reliable [411].

- The effectiveness of supervisory control strategies for scheduling is described in [881]. In [882] the same approach is used for flexible manufacturing workcells. It is demonstrated that nothing more is required than mapping tables of controlled automata or Petri Nets.
- In the discrete-event systems, methods of supervisory control turned out to be convenient for checking the consistency of hierarchical architectures [883]. This is one of the novel methods developed by the W. Wonham's school [75].

Task Decomposition

The concept of task decomposition was first introduced by J. Albus in [380], and described in detail in [412]. M. Arbib presented supportive ideas in [413]. Substantial contributions into the task decomposition paradigm were made by their followers, D. Lyons [414] and R. Simmons [415]. The ideas of task decomposition descend from the framework of automata theory [942], and can be easily transformed into computer language, which was done by J. Ish-Shalom [416]. These ideas allow for easy applications in the control hierarchy. Further theoretical development in the area of hierarchical automata decomposition is presented in [578]. In [417] the results of the research in task oriented planning performed by P. Fiorini and J. Chang are described. Some of the results of planning research accomplished by NIST fall into the same category [420-422].

Task decomposition and even hierarchical task organization became an unavoidable stage of each effort associated with large complex systems. In [418] the results of using this framework and the corresponding planning system are described for the Space Station Freedom. In [419] the task decomposition of "grasping" was explored and mathematically analyzed.

Task decomposition fits within the duties of Job Assignment and allows both spatial and temporal search for the best plan similar to the RCS arrangement [423]. Nested decomposition of functions can be incorporated by the methodology of colored Petri Nets [424]. The paradigm of tasks decomposition naturally combines motion analysis and scene representation and easily fits within the framework of fuzzy logic, analysis and control [425]. No change is required in the multiagent case. In [426] the configuration description language CDL is introduced for task analysis based planning in a multiagent case. Analysis of reasons for the multiagent case requires performance of particular operations similar to those applied in the justification based Reason Maintenance System [822, 823]. Very similar approach and results are presented in [427]. In [428], J. Budenske and M. Gini demonstrate persuasively that the task decomposition paradigm allows for adding all required information about sensors and control rules.

The whole topic of task decomposition and associated kinds of logic are paralleled by the corresponding developments in the area of entity relational databases and knowledge bases. Within this domain, task decomposition is a result of so called "structured task analysis". Well organized technique of structured task analysis is presented in [909]. Control systems equipped with these types of databases with various types of logic and optimal learning are described in [429, 430]

Geometric Models for Planning

This domain is strongly linked with practical problems. It also generates a variety of famous theoretical problems: the "sofa" problem evolved into "piano-movers" problem. A thorough survey is given in [431]. An interesting geometric model based upon Snell's law is presented in [432].

The efforts in constructing geometric models were related to obtaining collision-free robot paths. In some papers [433] these efforts are associated with V-Graph algorithm that was first proposed by T. Lozano-Perez in [381]. We associate the bulk of works on geometrical models with a different theoretical avenue, which is presented in [434-436]: all of these works use the concept of space tessellation. Also, geometrical planning was correctly considered to be a part of the problem of optimal control, however, the analytical solution recommended in [437] was a very difficult one, and computational rule-based algorithms like the one presented in [438, 439] gave designers a multiplicity of new practical tools. These methods were extended into a hierarchical domain and became a part in RCS reference model architecture [440, 441].

Most of the FINDPATH algorithms of the 80s are based upon searching for a minimum path string of vertices within the so called "visibility" graph (a graph comprising all vertices of the polygonal objects connected with visibility lines [439, 442-445].

It would be instructive to scan the evolution in this area during the last decade.

- Some intention is expressed to avoid using any planning algorithm in favor of sensor-actuator "agent" unit. This will be focused upon later in a special sub-subsection on Visibility-Based Planning. An example of simple solution is given in [446].
- An example of applying VGraph concepts via 3-D space decomposition is described in [447].
- A synthesis of 2-D formulated algorithms of path planning from [434-436] and 3-D VGraph concept from [381] is demonstrated in [448].
- Further development of the algorithm from [448] is presented in [449]. These results use representation of obstacles as polyhedral cons. A productive idea called "Window Corner" is introduced that allows for using a breadth-first search strategy.
- A new method of space transformation is proposed in [450]. It is different from configuration space of [379] and from visibility graph of [438]. It allows for motion planning of a robot which moves with translations and rotations .
- An intention to find a single winning rule for most of the situations demonstrates itself in [451]. Different strategies for reactive navigation were proposed.
- A further development of the overall-planning paradigm is undertaken in [452]. An effort is made to blend together VGraph-like concepts with the existing results in planning within multiple traversability spaces [453].
- The need to cover planning for multiple degrees of freedom is reflected in [454]. In [455] a similar problem is addressed for anthropometric figures. Many researchers raise the issue of solving problems of on-line planning. This leads to the need for a joint space-time representation of motion processes and development of efficient methods of scanning a space of upcoming functioning [456-457].

Planning for Minimum Time of Functioning

When the cost of functioning is time then the time should be minimized. All problems of minimum time positioning are solved by using variation methods or Pontriagin maximum principle [458-459]. When positioning is done in the obstacle-cluttered environment, the method of slalom situations can be applied and all the past alternatives can be found as topological passageways, and the final solution is determined by using dynamic programming or searching in the state-space [460]. For the multilink manipulator this approach is explored in [461]

If minimum time is required while tracking the specified trajectory similar methods can be applied. The subtle differences are demonstrated in [462, 463].

Nonholonomic Path Planning

Most robots, especially mobile robots, can be considered single body devices (car-like robots) or comprised of several bodies (tractors towing several trailers sequentially hooked) [464, 465]. These robots are known to be nonholonomic, i.e. they are subject to non-integrable equality kinematic constraints involving the velocity [466]. This generates the need in hybrid control strategy especially for providing feedback stabilization [467, 468, 474, 475]. The number of controls is smaller than the dimension of the configuration space [469, 470].

Many cases of nonholonomic constraints are linked with the need of objects to be in contact [471]. The range of possible controls has additional inequality constraints due to mechanical stops, for example, in the steering mechanism of the tractor. The problem of finding the shortest path can be resolved for the case of bounded curvature [472]. A solution based upon a hierarchical controller is described for the free-flying space robot in [473]. Motion planning is compared with time varying control system in [476]. It is demonstrated for the nonholonomic multibody robots that the Controllability Rank Condition Theorem is applicable even when there are inequality constraints on the velocity, in addition to the equality constraints [477-478, 919].

Planning in Unknown, or Partially Known Environment

Planning in unknown environments is a problem that defies our orientation to derive the search process from the concrete knowledge of the environment. There are two fundamental approaches applicable for dealing with situations with limited and absent knowledge. One of them is linked with name of A. Willsky [479] and explores general evaluation of motion through random fields with a different fraction of stochastic component in the available information. Another direction is oriented toward finding a "good" strategy that works even if nothing is known about the environment. This direction is linked with the name of V. Lumelsky [480. 924]. Both strategies are linked with the need to make decisions in the presence of risk [481].

The strategy of finding a universal rule is more popular because it fits within a paradigm of forming reactive behavior [482]. Indeed, the map of a maze might be unknown, but the strategy of behavior in a maze should exist [483]. Even in the case of a multilink manipulator we can require having a "winning" strategy of actions under conditions of lacking or absent information [484]. Also, other ways of dealing with unknown environment are being explored [485, 486]. Yet, there is an area of research oriented toward finding the most general rules of dealing with different types of environment [487-489]. By and large, the research in this area converges to the

hierarchical schemes of world representation [490] and focusing attention with the help of a concept of "virtual window" [491].

Planning in Redundant Systems

Non-redundant systems have a unique trajectory of motion from one state to another. A redundant system is defined as a system in which more than one trajectory of motion is available from one state to another. It can be demonstrated for many realistic "system-environment" pairs that they have a multiplicity of trajectories linking an initial state to a goal state, and these trajectories can have different costs. These systems contain a multiplicity of alternatives of space traversal. An example with a multi-limb robotic system is presented in [492], and an automaton proposed to deal with this case is described in [493].

Redundancy grows when the system is considered to be a stochastic one. The number of available alternatives grows even higher when a multiplicity of goal tessellata of a particular level of resolution is also considered under the condition of assigning the goal at a lower resolution level, which is the fact in multiresolutional systems such as RCS [494, 495].

In non-redundant systems there is no problem of planning: only one trajectory of motion is available. Since the trajectory of motion to be executed is a unique one, the problem is to determine this trajectory and to provide tracking of it by an appropriate control system. Many research results demonstrate that redundancy can be considered an important precondition a) for the need of planning, b) for performing planning successfully [496-499].

Planning for Situations with Moving Obstacles

This group of results is actually an evolution of the domain of redundant systems. The roots of strategies for solving collision–free trajectories are derived from the search in configuration space [381, 500]. Complexity of these algorithms is evaluated in [501]. Within the framework of control theory, the collision-free trajectories were obtained by sewing together convenient pieces of analytically represented trajectories [502]. Also, optimality was not necessarily provided.

The problem of dealing with multiple robots can be resolved within the unified approach from [503]. The evolution of this methodology within the domain of moving obstacle path planning was performed by R. Conn and M. Kam [504]. The results of computation do not provide the optimality of motion.

Planning for Multiple Robots

This is a further development of the topic with moving obstacles. However, this is a more complicated subject because each of the robots has its own goal, and all these goals must be achieved under some conditions of total optimality. The optimum motion planning for multiple robots with independent goals is presented in [890]. This technique descends from the configuration space approach, uses the Game Theory for decision making, and allows for multiple resolution application. The simplified case of the optimality is related to the requirement of cooperation. In [505] it is demonstrated that time scaling can be applied beneficially.

If planning is based upon task decomposition (see e.g. [415]) then for a two-arm manipulator system the solution of the problem is described in [506]. The need for exhaustive search can be avoided by using multiple heuristic rules, which check interference between different sub-systems of the manipulator, and apply the collision-avoidance strategy of planning incrementally [507]. The condition of minimum time would require using one of the known analytical techniques like in [508]. New heuristics can be learned during the process of planning before the motion actually starts [509].

CMU suggests resolving the problem of multiple robot planning by using the D* algorithm [510]. The latter is a modification of the A* algorithm when the algorithm functions on-line in unknown environments [511]. The authors call their algorithm D*, in a sense dynamic A*, please note, that this term dynamic has nothing to do with dynamics of control, or dynamics of mechanical motions. It means solving the problem on-line while the situation changes.

In [512] a multiresolutional scheme is proposed for multiple robot control and in [914] for planning in a rough terrain without references to the existing literature on multiresolutional planning. Schemes of local searching for multi-manipulator situations are explored in [513]. In both [514] and [515], the effort is made to provide for meaningful multi-robot behavior by using the concept of reactive control. Various methods of force distribution turned out to be important for solving this problem [574]. A promising architectural paradigm applicable for mobile robots is presented in [942].

Multiple robots can be considered within the framework of the theory of cooperative robotics, which first was outlined as a field of distributive artificial intelligence [891]. A similar but more advanced, framework was proposed by T. Fukuda and S. Nakagawa [892]. This was used as a theoretical basis for the development of cellular robots (CEBOTs) [893, 894]. J. Beni proposed the concept of SWARM, which represented the self-organizing swarm type of environment [895, 896]. The distributed system of control ACTRESS was developed by providing cooperation among multiple robots [897]. SWARM consisted of a very large number of robots; CEBOT allowed for smaller number of robots-participants; ACTRESS was created for groups of several robots. The smallest amount was allowed by the concept of GOFER [898]. Comparison of all architectures is given in [899]. The taxonomy for multiple robots system was proposed in [900].

Uncertainty and Probabilistic Techniques for Path Planning

From the very beginning of the era of Intelligent Control and Robotics, errors in functioning were admittedly the worst enemy of the development of this area. Control system specialists knew the difference between noise, disturbances and errors, however, they were not always successful in counteracting these factors. The problem of compliance emerged immediately with the birth of the first industrial robot. The argument was: "We cannot stop exactly against the hole, thus, the construction should be compliant to compensate for this mistake." One of the techniques of providing compliant motion is described in [516].

Most of the techniques for searching the minimum-cost paths on the graph are deterministic ones, and introduction of uncertainty became a new source of challenge [517-519]. An approach to motion planning with uncertainty for mobile robots is introduced in [520]. Given a model of the robot's environment, a "sensory uncertainty field" (SUF) is computed over the robot's

configuration space. At every configuration, the SUF is an estimate of the distribution of possible errors in the "sensed configuration" and it is computed by matching the data given by the robot sensors against the model. A planner is using SUF to generate paths minimizing the expected errors. SUF has been explored for a classical line-striping camera/laser range sensor.

It is typical to use fuzzy sets for evaluation of uncertainty. In [521] an interesting example is described which combines flexibility of fuzzy sets as a tool of evaluating uncertainty and Petri Nets as automata technique for computing plans. In [915], an implementation of probabilistic techniques to the problem of path planning is demonstrated.

Online planning relies on information that becomes available to the sensors during execution, to allow the robot to correctly identify the states it traverses. The set of states should be chosen; the motion command should be associated with every state, and the state evolution should be evaluated. The interdependence of these tasks can be avoided by assuming the existence of landmark regions in the workspace, which could be considered "islands of perfection," where the position sensing and motion control are accurate [522].

Algorithms of Planning

Planning constructs the goal states, and/or the preferable strings of states connecting the present state with the goal states. One of the successful techniques is associated with task decomposition [415]. Task decomposition is related to the consecutive refinement, i.e. to consecutive increase of the resolution of representation for both actions and states. Hierarchical planning which originates in task decomposition is described in [925]. The first component of the planning algorithm is translation of the goal state description from the language of low resolution to the level of high resolution. Frequently, it is associated with increasing the total number of the state variables. In all cases, it is associated with increasing the scale of representation, or with reduction of the indistinguishability zone, or the size of the tessellatum associated with a particular variable.

Each algorithm of planning should start with finding the objects of attention which are usually points in the space that will be used as the feature nodes of the search-graph. When these points are chosen as the nodes of a coordinate grid the result of search can be unsatisfactory because of idiosyncrasies of the alternative trajectories as described in [453]. As an improvement, it is proposed that these nodes be shifted by adding or subtracting the random value value to or from the coordinates of the node [523, 524]. Otherwise, all points should be distributed randomly as suggested in the original paper [109].

Search has many alternative algorithmic choices. In some of them, the A* algorithm is used [375, 376]. It is known that the A* algorithm is computationally more efficient than exhaustive search. This is why it was selected as a prototype for many other solutions, e.g., the D* algorithm [511]. Nevertheless, in the most advanced versions of search algorithms, applied in practice [525, 526], the decision was made to use the exhaustive search and its Dijkstra incarnation. The reason for this is the peculiarity of A* in non-linear systems. In the space divided into multiple segments with different traversability, the A* algorithm can be easily confused. Since in most planning systems the reduction of complexity is taken care of by using a multiresolutional paradigm, Dijkstra-search should be recommended as the best practical solution.

The second component is the simulation of all available alternatives of the motion from the initial state, IS, to one or several goal states, GS, and selection of the "best" trajectory. Procedurally, this simulation is performed as a search, i.e. via combinatorial construction of all possible strings (groups). To make this combinatorial search for a desirable group more efficient, we reduce the space of searching by focusing attention, i.e. by preselection of the subset of the state space for further searching.

In a limited number of works, some of the designers choose "greedy" algorithms which require neither evaluating the total cost from the beginning, nor evaluation the total cost to the end. Search based upon "greedy" algorithms is frequently deceptive because the final trajectory obtained is a result of local preferences. This is the case recommended in [527]. Many recommendations using the concept of simplified dynamic programming are based upon computing only local costs and have the same limitations as "greedy" algorithms. Some examples of planners with neural network based local cost evaluation are given in [528, 529].

Methods of determining node candidates in a polygonal world are presented in [922]. Methods of planning in the cases of redundant manipulation are described in [920]. Thus, all planning algorithms consist of two components: a) a module for exploration of spatial distribution of the trajectory, and b) a module for exploration of the temporal distribution. No algorithm of planning is conceivable without these two components.

The need for planning is determined by the multi-alternative character of the reality. The process of planning can be made more efficient by using appropriate heuristics determined by the specifics of a concrete design specifications.

Local Planning: Potential Field for World Representation. Genetic Search.

The most pervasive method for navigating with minimal planning effort is using potential field construction around the obstacles [530, 531]. Potential field presumes adding to the world representation properties that will increase the cost of moving in particular directions. An approach to robot path planning is proposed in [532] consisting of building and searching a graph connecting the local minima of a potential function defined over the robot's configuration space. The planner based on this approach allows solving problems for robots with many more degrees of freedom. The power of the planner derives both from the "good" properties of the potential function and from the efficiency of the techniques used to escape the local minima of this function. The most powerful of these techniques is a Monte-Carlo technique that escapes local minima by executing Brownian motions. The overall approach is made possible by the systematic use of distributed representations (bitmaps) for both the robot's workspace and configuration space.

Genetic search is one of the tools for local planning. In some environments it gives positive results and can be recommended for use [533, 534]. The concepts of receiving smooth trajectories locally are presented in [921].

Global Planning: Search for the Motion Trajectories

After reviewing all the above solutions, one can see that the most general way of planning is by global searching. It consists of the following stages:

1. Populate the World with randomly assigned "points" that become vertices of the search graph.
2. Connect them in the vicinity (neighborhood); this reduces the graph connectivity.
3. Determine the cost of edges.
4. Run the graph search algorithm (e.g. Dijkstra algorithm or A*).

There are some problems that can be resolved in each particular case. Indeed, the "density" of future vertices of the search graph has to be selected. The concept of "vicinity" ("neighborhood") should be discussed, and its value should be properly evaluated. Different techniques of pruning the search-tree should be discussed. This area is explored in [535-539].

Several randomized path planners have been proposed [540, 541]. They are recommended for a variety of robots. A general planning scheme is introduced that consists of randomly sampling the robot's configuration space. The choice of candidates to become graph nodes can be determined by a relation between the probability of failure and the running time. The running time only grows as the absolute value of the logarithm of the probability of failure that we are willing to tolerate.

Architectures for Planning

All earlier architectures anticipated the need in a hierarchy derived from the primal decomposition—spatial and or temporal [380, 542]. A multiresolutional hierarchy was anticipated in [412, 109], and then described in [130, 543, and 544].

Behavior based architectures are described in [545] where two different behaviors are blended. A rough, superficial, quick one was blended with a thorough, precise, slow one. For both behaviors some local generalized representations were required. Description of a similar architecture is found in [555]. The concept of blending behaviors has demonstrated its benefits so far only in small scale problems. Its exploration started long time ago [556]. In [546] blending is explored for a different set of behaviors: reflexive, purposive and adaptive. In this case the goal of the architecture was to avoid representing the world.

The architecture of decision-making is implied by the principle of hypotheses testing as demonstrated in [547]. Some of the architectural solutions do not have an explicit structure of consecutive refinement; many researchers prefer to talk about general purpose planners and specialized reasoners [548]. Obviously, in this case we deal with a nested multilevel decision making.

The researchers in the area of fuzzy sets gradually arrived at nested hierarchical solutions presented in terms of fuzzy control theory [549]. L. Zadeh anticipated nesting of fuzzy control rules in 1973 when he suggested some special rules of inference [550]. Hierarchical fuzzy controllers are now broadly proposed for robotic manipulators [551]. The general characterization of these controllers can be found in [544]. Analysis of the role of hierarchical design for fuzzy logic controllers is described in [579]. A similar hierarchical architecture based upon neural networks is presented in [580].

Architectural issues are entering the focus of attention in the area of control [552]. Comparison of several versions of cognitive architectures is given in [553]. Software issues are addressed in [554]. Software questions of real time hierarchical control have been analyzed in [577].

Applications of Planning Methods

The following applications are presented in literature:

- Trajectory Planning for Spray Painting Robots [557]. The motion is planned so to provide the fastest coverage of the surface with reliable overlap of the brush strokes.
- Planning for Flexible Manipulators is based upon computing total manipulator strain energy and motion evaluation along the elastic coordinates [558].
- Planning has been developed for dexterous manipulators with sliding contacts. Polygons where sliding may occur are computed based upon geometrical and mechanical consideration [559]. The required friction to control the sliding is computed.
- Motion of spider-robots is planned taking into account the configuration of multiple legs while maintaining stability [560].
- Planning for the job-shop boils down to determining a rational schedule. The stochastic cases are considered in [561]. Network application for the same problem is demonstrated in [562].
- Stewart Platforms have specifics planning challenges: multiple parallel actuators have to develop mutual coordinated motion following a particular preplanned trajectory [563]. Using search for solving this problem is recommended in [564].
- Many papers in the area of planning are dedicated to flexible manufacturing. Stability and performance for a stability case is addressed in [565]. Utilization of Petri Nets is demonstrated in [566]. Blending Petri Nets and Heuristic Search is described in [567]. The whole cell control is analyzed in [568]. Performance and dependability are jointly analyzed for cellular manufacturing systems [576]. Fuzzy decision making for scheduling is proposed in [569]. Knowledge-based approaches are addressed in [575].
- Part of the planning for computer integrated manufacturing systems is the robot selection and workstation assignment (RSWSA). RSWSA seeks an optimal mix of robots to serve all given workstations such that each workstation's resource demands are satisfied, no robot capacity constraints are violated, and the total system cost is minimized. In [570], in order to roughly determine the initial feasible solutions, the "greedy" algorithm is applied, and then the solution is improved analytically.
- An example for using similar methods of planning for large scale marketing channels in the tile industry is demonstrated in [571].
- For simplifying complex air traffic control problems the motion of the airplane is fuzzyfied up to the level of salient maneuvers description [572]. Each of these maneuvers invokes a separate process of planning, which is described in [573].

Planning for Assembly Operations

Assembling is a more general job than path planning. Actually, solving the task decomposition problem together with corresponding path planning procedures form the complete assembly operation. Initially, papers related to assembly operations focused upon the so called pick-and-place operations. Designers were concerned with performing these operations in a smooth manner, and spline-sewing the trajectories was a conventional approach [582]. The complete fundamental methodology of planning the sequence of assembly operations can be

found in [583]. The computer algorithm for automated development of assembly sequences is described in [584].

The richness of the environment makes assembly procedures very amenable to the techniques of knowledge engineering. The process planning for electronic assembly is described using information organized in a knowledge base [585]. Even the sensing procedures should be specifically planned in the assembly environment [586]. NIST started working on a part of this issue (planning of the inspection) [587]. The very process of assembly planning should be equipped by the feedback loop and visualized as a multiscale enterprise [588, 589]. Integration of planning and control is in the focus of attention of researchers [929].

Many issues have emerged in the practice of applying planning algorithms in assembly. It would be interesting to see what kind of issues can be anticipated in similar cases in other areas.

- Forces in the gripper should be taken into account during the path planning of a manipulator [590].
- The assembly sequence planning is affected by the elements of human participation at the particular stages of assembly [591].
- An effort to automate the process of assembly programming based upon solely logical rules was demonstrated in [592, 593]. However, the consistency of the purely logical type of approach was shown only for simple cases.

An experience of multiple robot assembly in [594] has illustrated that most of the functioning processes were based upon strong reliance on heuristics taken from direct human experience.

- The difficulties in using logical sequences demanded further development of the temporal framework for representation; some results were presented in [595].
- In [596], it was demonstrated that planning of the assembly requires performing stability analysis.
- For assembly planning in systems with visual guidance, special techniques of calibration were proposed in [597]. (More on the systems with visual guidance see in Section 6)
- The theory of constraints in assembly planning was proposed in [598].
- special problem of assembly planning in which the sole action of pushing is used is addressed in [599].

5.2 Execution

After the plan is developed, it is submitted to the subsystem of execution. The latter determines the inputs that should be generated and submitted to the actuators. Typically the inputs are found by applying the operator of "PLANT-INVERSE" to the plan. In most cases the analytical representation of a plant is invertible because all plants are stabilized before the planning started. If the plant is assigned not analytically but as a computational algorithm the inverse algorithm is easy to obtain.

The input to the actuators obtained as a result of inverse is incorrect, because the plan is computed without knowledge of the situation and has errors, because the model contains sources of disturbances, and because the whole system is subjected to many sources of noise. Thus, the EXECUTOR contains the subsystem of feedback compensation that compares the planned trajectory with the real trajectory and computes the signal for compensation.

In order to do this, the current signals and parameters should be estimated and even predicted. All these components of the executor can be realized in a different way, some of the popular solutions are presented below. Actually, the problem of integrating planning and control is a problem of constructing the corresponding multivalued logic [927].

Popular Solutions

- The concept of joint feedforward/feedback organization of the controller came into broad practice in the 80s. In [600] the continuous system with the near-optimal function is analyzed.
- This type of solution needed reliable methodologies of simulation that were performed sometimes by backward differentiation [601], or in the cases of important constraints, by a diligent geometrical analysis [602].
- The feedforward/feedback setup was recommended in all systems in which an externally given plan was supposed to be "tracked" [603].
- As soon as this simple conceptual approach was supposed to be applied in multilink manipulators, the situation became more complicated. First, the input was always formulated in the terms of torque in order to escape the need for modeling the dynamics of actuators. Nevertheless, even in this case the problem was difficult and required solving a non-linear optimization problem using knowledge of the Jacobian of the constraints and the gradient of the objective function. Second, it was clear that using only information of joint torques was not enough, and jerk constraints were introduced [604]. Jerks as inputs are proposed in [458].
- The ability of encapsulate various problems into a single model led designers to the decision to use adaptive robust control systems similar to the one presented mathematically in [605].
- If the functioning was a combination of discrete events, the framework was available for sequential or even concurrent simulation [606]. This paradigm could be utilized partially for continuous control systems equipped with discrete time observers [607].
- Still the unmodelled dynamics played a substantial role. It was addressed either by using fuzzy logic controllers [608] or constructing compliant systems [608, 609]. In some cases, designers were taking measures to provide smoothness of motion for the trajectories that were inadequate. A popular tool was minimization of acceleration at critical points [610].
- Finally, various modifications of well known controllers were implemented:
  a) Controllers with gain-scheduling [611];
  b) Fuzzy PID controllers [612];
  c) Analog-digital fuzzy logic controllers [613];
  d) Sliding mode fuzzy controllers [614, 619];

e) Controllers with prediction [615]; prediction and adaptation in PID controllers was addressed in [620];
f) Various Neuromorphic Controllers [616, 617].

Among the practical design methods utilized for all controllers, a family of methods emerged using various approximation techniques especially in the state-space representation [618]. Non-linear methods of design become popular, too. A non-linear design for the sliding mode controller is described in [621].

Properties of Controllers

- A survey on the controllability of fuzzy logic controllers is presented in [622].

- Methods of stability analysis for controlling the flexible multi-body system is presented in [623]. Stability of muscle-skeletal systems is analyzed in [624]. Analysis of the stability of a robot under model mismatched conditions is given in [625]. Stability in a fuzzy controller is addressed in [626, 937, 938].
- Optimum control of production rate is presented for a manufacturing system producing a single commodity. The author focuses on finding two factors of optimality, optimal policy of control and optimal inventory level [627]. Time optimal control systems for the point-to-point motion continue to be in a focus of attention of the researchers [628].
- The issues of performance and how to improve it are described in [939].
- The desire grows to characterize control systems by a longer list of specifications. The following factors are considered candidate components of the vector of specifications.
  a) Accuracy and stability of voluntary limb movements [629]
  b) Accuracy and stability in redundant systems with flexible components [630]
  c) The profile of error of tracking the planned trajectory [631]
  d) Robustness against the modeling error [632]
  e) Measure of connection between variations of control parameters and the time of response [633]

Applications

We will start with listing applications of numerous moderately intelligent systems and then will focus on more intelligent visually guided control systems (mobile autonomous robots and autonomous systems are presented in a separate section).

- OSU has developed a nonlinear controller for a two-link flexible robot that is equipped with an acceleration feedback [634].
- JPL proposed a neuro-controller for redundant multilink manipulator which can be directly applied as an executor for a system with obstacle avoidance [635].
- Another JPL result is a controller for an advanced tele-operator that allows for convenient cooperation between a human operator, the master arm and the slave arm [636].
- The same research group developed a controller for a dual arm system. This controller reconfigures itself depending on a task which should be performed [637].
- A distributed controller was developed in a joint effort between Belgian and German universities. It controls a system with distributed parameters better than is allowed by existing solutions with non-linear filters [638].
- Another group at JPL has developed an intelligent controller for joint manipulation of two arms grasping the same object simultaneously. It presumes upper level planning and it develops a high level of cooperative compliance [639]. A method of extending the task space control is described in [640].
- Training simulators is an area where intelligence must demonstrate a high level of compliance. A controller with three loops was developed at JPL which allows for extremely high levels of compliance in response to a variety of forces [641].
- In some cases the whole set of requirements cannot be provided just by the planning or execution subsystems. In this limited number of cases part of the intelligence should be delegated to the actuator. A sophisticated actuator was developed at JPL. It allows a range of strokes from three centimeters at a frequency of 1Hz down to .2 cm with frequency of 1kHz. The accuracy of controlling the length of the stroke is .0001 cm [642].

- The problem of welding is one of those for which the appropriate intelligent controller has not yet been fully developed. In [928] a system with predictor of properties and variables is decribed. At the J. C. Marshall Space Flight Center a system for automated welding has been proposed. It takes into account the following factors: seam configuration, weld real time model, weld computer controlled parameters, wirefeed control with assigning position by feedforward and feedback, multi-access motion, torch rotation with plasma control, and bead profile [643].
- Kyoto University, Japan has developed a controller for a master-slave manipulator with high quality coupling. Theoretical analysis and experimental results are given in [644].

Visual Guidance

Visual Guidance is an intermediate step toward partial and/or total autonomy[3]. It emerged in order to increase the intelligence of control system without requiring creation of a rich world representation system, several levels of planning, and multiple learning capabilities. Visual guidance is oriented toward creation of a "minimalist smartness": the ability to perform smart and agile motion using minimal control tools. The following are examples of visual guidance.

- Probably, the first results on visual servoing were developed by A. Sanderson and his students in 1983-84. Practical results for visual servoing for two cooperating manipulators are presented in [645]. Two cases are discussed: a) with static camera and b) with dynamic sensor placement. An effort was made to optimize the system under multiple objectives.
- Visual guidance in manipulation is usually coupled with the operation of grasping [941]. The results of developing a system for visually guided grasping are presented in [646]. The authors focus on their goals of making the system applicable in unstructured environments.
- Visual compliance is the most widely used area of visual guidance. Indeed, compliance usually presumes solving local problems dealing with errors. In [647] a control system for visual compliance is described, which was tested for grasping operations using a PUMA robot.
- Further development of the visually guided grasping is presented in [648]. It was demonstrated that the effort is successful when two cameras are involved in a visually guided control loop, and both cameras are calibrated.
- An example of visual guidance of a mobile robot is given in [649]. The system can perform obstacle avoidance using single camera vision and ultrasonic sensors. It invokes necessary rules within a relatively uncluttered environment where all possible combinations of visual artifacts are pre-interpreted.
- The subtle and very important issues of jointly calibrating the camera and the performing machine are analyzed in [650] for the case of hand-eye visual guidance. Sensitivity analysis made the methods of non-linear optimization applicable to the intelligent controller.

The "intelligent observer" (IO) is introduced in [691] as a mobile robot which moves through an indoor environment while autonomously observing moving targets selected by a human operator. The robot carries one or more cameras, which allow it to track objects while at the same time sensing its own location. It interacts with a human user who issues task-level commands, such as indicating a target to track by clicking in a camera image. The user could be located far away

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[3] Certainly, the kinds of guidance are possible using other modalities of sensing. We focus here upon visual guidance as a rich and representative example of the sensor-based guidance.

from the observer itself, communicating with the robot over a network. As the IO performs its tasks, the system provides real-time visual feedback to the user. A prototype of the IO has been implemented, which integrates basic versions of four major components: localization, target tracking, motion planning, and robot control. Initial experiments have been performed using this prototype, which demonstrate the successful integration of these components and the utility of the overall system.

A particular problem of computing robot motion strategies is outlined in [692]. The task is to maintain visibility of a moving target in a cluttered workspace. Both motion constraints (as considered in standard motion planning) and visibility constraints (as considered in visual tracking) are taken into account. A minimum path criterion is applied. Predictability of the target is taken into account. For the predictable case, an algorithm that computes optimal numerical solutions has been developed. For the more challenging case of a partially predictable target, two on-line algorithms have been developed that attempt to maintain future visibility with limited prediction. One strategy maximizes the probability that the target will remain in view in a subsequent time step, and the other maximizes the minimum time in which the target could escape the visibility region.

Recently, it was demonstrated that image flow can be used for local obstacle avoidance. The results of this advancement are presented by NIST in [913]. Other techniques of using optical flow for recovery of relative motion, and, eventually, for navigation are described in [916].

I.6 Intelligent Control of Mobile Robots

Surveys of Architectures of Intelligent Vehicles can be found in [540, 693]. In the subsequent subsections only those materials that appeared during the last decade or those omitted from the surveys because of its scope limitations are included. The organization of this section is influenced by the recent results on autonomous mobile robots [495].

6.1 General Issues

Before the 80s control of vehicles was not a central issue in the literature of automatic control. This domain is also full of unsolved problems related to optimization [694]. In order to determine the trajectory assigned for tracking, a plan was submitted, and the first approaches to planning were based on analyzing the map by image analysis techniques [695]. In both articles mentioned above the problem was to be solved by human supervisors. In [696] the whole process of planning and navigation was analyzed in a manner that suggests automation.

The problem of navigating an unmanned mobile robot through a 2 1/2D-World was addressed in [697]. A symbolic structure was used with iso-elevation lines in the map. Most of the issues of updating the sensor-based map from the image flow were described in [698]. A detailed analysis is presented in [913]. Part of this material was incorporated later in 4D-RCS [495]. The concept of 4D-RCS Architecture was a synthesis of the 4D-approach of dealing with image sequence understanding [812] and of RCS.

In [699] it was demonstrated that motion practically doesn't affect dynamic equations of two manipulators installed on the same mobile platform and performing cooperative functioning. The

issues of steering were addressed in a number of papers: with a proposed control theoretic model of driver-steering behavior [700], with the dynamic equations of steering control [701], with a different number of wheels that perform the process of steering [702].

A set of theoretical developments was related to motion planning of intelligent vehicles. Various combinations of polygonal obstacles with polygonal a vehicle were analyzed in [703], and the value of complexity was evaluated for computing graphs of interaction between vehicle and environment. The evolution of this work has resulted in algorithms that structure space for planning software [704]. It was understood that planning should play the anticipatory role and algorithms for path prediction were developed in [705].

A substantial part of intelligent vehicle control is dependent on its on-board communication: the communication bandwidth strongly affects the results of map updating and therefore the results of navigation. This dependency was analyzed in [706] and algorithms that implement preferable strategies were proposed.

A formidable problem of all intelligent vehicles is perception of the 3D world around them. Automatic stereo triangulation or stereo vision is an attractive approach to on-board range finding. L. Matthies and C. Anderson in [707] proposed a mathematical analysis, some analytical models and computational algorithms. Fusing sonar and vision based measurements for topological mapping of intelligent vehicles is described in [708]. The significance of constructing landmarks was emphasized in [936].

In the period of 1985 through 1995 many research groups were working on coordinating movement and manipulation for a mobile robot equipped with a multilink manipulator. A good integration of prior research is presented in [709], where results are obtained for a PUMA installed on a LABMATE mobile platform.

In recent years, attention has been devoted to the study of vehicle motion. Numerous papers have been published on the topic of motion control of nonholonomic systems. These include works by Brockett and Dai [723], Samson [724], Murray and Sastry [725]. Many have also been the publications in the field of motion planning of nonholonomic systems. J.C. Latombe's publication on robotic motion planning [726] and the subsequent collection of works published by Laumond [727] show extensive research in the field of planning of optimal trajectories.

Nevertheless, a detailed model of the dynamics of a vehicle, with rear propulsion and front steering, is never represented. Very often, actuator dynamics are considered as unmodeled dynamics. In most of practical cases this assumption is unnecessary: the dynamics of actuators is known. This assumption prevents one from understanding the effects of the coupling properties present within the system. It would be desirable to have more precise representations of vehicle dynamic systems by taking into account the combined behavior of the actuators for propulsion and steering. Only after such model is derived, a planning algorithm can be proposed based on state-space search for trajectories that minimize a cost. In the literature, one can find only the preparation to solving the real problem. Problems of World Model maintenance are addressed in [933]. Multiresolutional issues involved in updating the world representation are addressed in [934]. The problem of consistency for knowledge-based representations is described in [935].

Planning in intelligent vehicles with nonholonomic constraints has created a new set of research results. G.-P. Laumond's research group has contributed novel algorithms tested in mobile robots of the Hilare family [710]. Nonholonomic camera-space a manipulation is addressed in [720]. A technique of nonholonomic planning for a vehicle moving among obstacles is presented in [721]. In [722] systems having holonomic and nonholonomic constraints are compared.

The following research results, which appeared over the last three years, should be mentioned:

- In 1996, a control architecture for automated guided vehicles was proposed that employs feedforward control jointly with a predictor-corrector scheme [711].
- In 1997 a technique for hierarchical refinement of skills and skill application was proposed for intelligent vehicles by M. Kaiser and R. Dillmann [712].
- E. Tunstel, T. Lippincott, and M. Jamshidi from the NASA Center for Autonomous Control Engineering demonstrated and tested the hierarchy of fuzzy rules that are required for generating consistent behavior of an intelligent vehicle.
- It was demonstrated that a planner-navigator based upon evolutionary programming allows for "near-optimal" planning results. In [714] algorithm was proposed with all components: the chromosome, the initialization process, the evaluation function, and the operators used.
- In 1997 several important results were obtained related to the further development of fuzzy controllers as applied to intelligent vehicles. In [715] the design methodology is presented for stabilizing a fuzzy controller applied in an articulated vehicle (which changes its configuration during the motion). One more scheme of fuzzy controller for collision avoidance is presented in [716] actually repeating the results from [453]. A combination of fuzzy controller with genetic algorithm was presented in [717].
- In 1998 several important results were obtained in the area of representation for intelligent vehicles. In [718], a system with triangular tessellation was applied for hierarchical world modeling. In [719] an evidential approach is applied to world representation of an autonomous vehicle equipped with sonar sensors. Novel results obtained at NIST for a multiresolutional world representation are given in [972].

6.2 Indoor Mobility

The first indoor robots with autonomous navigation were created for research and educational purposes. One of them, HERMIES-IIB (Hostile Environment Robotic Machine Intelligence Experiment Series IIB), was used for testing navigation algorithms at Oak Ridge National Laboratory [801], another, DENNING, was used by CMU for testing purposes [802]. The third robot was LABMATE whose descendent HelpMate has successfully survived until now (the description see below). "Aimy" was developed recently for studying navigation processes with an infrared detector system [810]. Another education oriented robot is Nomad 2000, which combines features of both DENNING and HERMIES. NOMAD was used also for testing TESEO, a neural network based computer system with generalization capabilities. This will be focused on in Part II of this report, in the section *Learning* [42].

Papers surveyed in this subsection cover the period from 1990 to 1999 and represent the evolution of numerous results described previously in Section 5.

- In 1990 A. Arkin and R. Murphy presented the results of indoor application of their earlier research results obtained in the Georgia Tech Laboratory for Mobile Robotics [729]. They

built upon prior results by G. Giralt and R. Chatila at LAAS-CNRS (France), U. Rembold at the University of Karlsruhe (Germany), D. Allen at the Cranfield Institute of Technology (UK). The goal of the effort was to demonstrate docking behavior and ability to navigate in a cluttered environment. The concept of the intelligent controller implements the authors' prior ideas of blending multiple behaviors and using potential fields. Joint functioning of the vision system and controller is described in [730].

- In 1991, G. Saridis' concept of three-level intelligent controller (organization, coordination, and execution levels) was implemented in the Petri Net coordination model that was tested in the indoor environment of comparatively complicated configuration [731].
- In 1992, the DARPA SIMNET, based upon a world representation acquired from the Defense Mapping Agency, allowed populating the virtual environment with a large number of autonomous vehicles called Semi-Automated Forces (SAF). The SAF human operator provides higher level supervision to the autonomous units, while lower level control, such as obstacle avoidance, formation keeping, bridge crossing, road following, etc., is the responsibility of the automated system. The SAF vehicles are simulated mobile robots operating in a complex environment driven by their intelligent controllers and manned simulators [732]. The present version of this system is called ModSAF.
- In 1993, D. Kortenkamp and his colleagues developed and tested the indoor mobile robot CARMEL. Their obstacle avoidance algorithm uses the vector field histogram (VFH). This algorithm creates a histogram grid that is a certainty grid representation of the objects surrounding the robot using the robot's sonar sensor [733]. The algorithm is based on an original psychological model of cognitive mapping applied to a mobile robot [734]. The theory of Stereo and Ego-Motion Mapping applied in this cycle of works is presented in [735]. Other works of the same group of authors can be found in [736-738].
- Very similar structures of control were reported in numerous papers during the period of 1994-96. Some of these works are presented in the terminological tradition of conventional control theory, come are described as fuzzy controllers. In [739] a mobile robot with ultrasonic sensor array demonstrated collision avoidance. By equipping the fuzzy controller with a neural network, the system becomes more sensitive and more agile [740, 741].
- In 1995, the HelpMate, the autonomous mobile robot courier for hospitals was reported [742]. It was a further development of the earlier products by Transitions Research Corporation (J. Evans and J. Engelberger). The architecture of HelpMate follows the RCS conceptual structure: it has modules of Planning and Execution, and its controller and the topography knowledge base as the World Model. It uses structured light for vision sensors.
- In 1996, the autonomous robot AURORA was demonstrated [743]. This robot is equipped with ultrasonic sensors and performs a regular job of spraying plants following a schedule.
- Following the pioneering results in [742] another hospital robot was proposed in [744], equipped with subsystems of learning for assignment acquisition and for obstacle avoidance. Teleoperation is recommended as a main mode of operation while automated tracking of the learned trajectory is attempted as a further development.
- The interest in "blending" behaviors still continued. The Oxford version of the robot with multiple behaviors was called distributed real-time architecture. Unlike the most of behavior-based architectures it is equipped with a meta-planner and demonstrates successful obstacle avoidance behavior [745]. Similar solutions were developed earlier by T. Mitchell [746], L. Kaelbling [747], and E. Badreddin [748], which differ from A. Arkin's results with blending of behaviors [749] by having upper level planning or a blackboard for prior simulation [750].

- An indoor robot, Robee, was developed for exploring visual behavior based on the centering reflex observed in freely flying honeybees [751]. This behavior is used to drive a robot through a corridor with parallel walls while controlling the forward speed and avoiding obstacles. Robee was produced using TRC LABMATE (see more in [742] and [752]). In the meantime, the HelpMate Robot has undergone further developments and is being manufactured by HelpMate Robotics, Inc. (http://www.helpmate robotics.com) of Danbury, CT. This is an intelligent system with a multilevel RCS-like architecture. Ten years of development of this intelligent commercial autonomous mobile robot are described in [753]. The design issues for intelligent mobile robots working in a healthcare environment are discussed in [754]. An application platform for development and experimental validation of the healthcare related mobile robots is described in [811].
- Another reflex-based control was tested for collision avoidance purposes [911]. This reflex is achieved by assigning protection zones around the robot and is similar to using DAR-zones ("dynamic avoidance regions") as described in [453, 970].
- In 1998 J. Borenstein described the OmniMate robot [755]. This robot is a multidegree-of-freedom mobile platform with omni-directional motion capabilities. The OmniMate was made at the University of Michigan from two LABMATE platforms. The results of this research allow anticipating nonsystematic odometry errors caused by bumps, cracks, or other objects on the floor.
- Another well-known indoor robot is the YAMABICO robot. It is equipped with both vision and ultrasonic sensors. In [649] its ability for self-localization was explored. Similar exploration of self-localization capabilities was investigated for the MACROBE [756], which is equipped with laser range finder [757]. In [902] it was demonstrated that active maneuvers have to support the processes of localization. The problem of self-localization was also explored in [758]. An indoor mobile platform Robuter was the testbed. This platform has a differential steering car-like kinematics and is equipped with an odometric system that supplies the a priori pose estimate. In general, the configuration of wheels and steering mechanism is of crucial importance for controller design. In [759] an omni-directional autonomous platform is described as an option for indoor application. A unique set of analytical expressions is proposed for this holonomic system.

6.3 Outdoor Mobility

Mobile Robots

In the 80s, there were only a few practical developments in the area of autonomous mobility.

- In the USA, the well known results that contained elements of autonomy were the experiments in road-following. These experiments were performed at Carnegie Mellon University on the vehicles NavLab and Terregator [760, 761]. Another outdoor mobile robot with a primitive path finding system and road following operator was created by FMC Corporation. It was a robot-tank [800].
- The experiments in on-line path-finding performed on IMAS (Intelligent Mobile Autonomous System) developed by Drexel University [540 and 762-764, 803, 804]. The IMAS solution [540] was based upon a multiresolutional controller with three levels of resolution: Planner-Navigator-Pilot. This architecture was analyzed [109] and further discussed in [762]. This concept was first introduced in [803, 804]. At the pilot level the "behavioral" controller utilized blending of two behaviors [970]:

a) those of a quick, shortsighted decision maker and
b) those of a farsighted, accurate decision maker [773].

- The experiments in outdoor autonomous security robot functioning designed by the Naval Ocean Systems Center were successful [765]. They allowed to clarify many requirements for "centry-robots" specifications."
- National Institute of Standards and Technology was involved in the development of the outdoor Field Material-Handling Robot based upon a precursor of the present RCS Architecture [808]. Early solutions of mobile robots can be found in [943-947].
- In Germany, the first vehicle with an autonomous system of control equipped with fast and efficient computer vision was put on the road in the end of 80s [766-768].
- In Japan, the first reports about autonomous vehicles appeared in the end of the 80s [769, 770]. Most of them have a very primitive control system which presumes tracking the path which was externally assigned.
- Most of the research in autonomous mobility was associated with the intention to improve the understanding of and testing the subsystems to be utilized and the architectures to be explored. In [771] an architecture is proposed extending prior solutions in vision guided motion. In [772] a control algorithm was proposed for the computer controlled vehicle system.
- Simple road following, which seemed to be so close to wall following, raised numerous problems of logical reasoning. These problems are engrained in the realistic context of the medium and are related to micro deviations in what should be considered as an edge of the road, macro changes in the edge, interruptions, puddles, etc. [774]. Evaluation of inconsistencies in representing a road edge is presented in [806]. Focusing Attention by active gaze control is described in [807]. The subtleties of controlling the complicated process of road following are described in [775]. The detailed description of the production system utilized for road following at the University of Maryland is presented in [776]. In the final version of their vehicle [777], this research group utilized the control system Planner-Navigator-Pilot with three levels of resolution. Another research result that utilized the Planner-Navigator-Pilot architecture was presented in [805].
- In the meantime, it was not so simple to execute the desirable curve under planned trajectory because the dynamics and kinematics of the propulsion and steering subsystems were not totally clear. In [778] the requirements for the "dodging" along the path are formulated for the case when a robot deals with moving obstacles. This problem has generated a multiplicity of research works that consider the links between steering and propulsion during the process of terrain navigation. The steering actuator dynamics were represented taking into account the first order lag of the steering actuator. The results were simulated, and the good quality of this model was confirmed in [779]. The processes of propulsion and steering were analyzed in [780]. These controllers should be supported by a proper estimation information [781]. The results improve, if between each pair of nodes in the string of the best plan, the shortest path is found on the surface of terrain [472]. The wind is taken into account in [782].
- A number of research results are dedicated to propulsion and steering of chained mobile systems, sometimes called "articulated vehicles". In [783] the results of design, analysis and control are presented for the Japanese articulated body mobile robot CORYU-2, which is composed of seven segments with total length 3.3m and total weight 330kg. Analysis of the steering controller for this vehicle is presented in [910]. Energy consumption has been

evaluated for different plans. General mathematical analysis of the chained mobile systems is given in [784], and the trajectory generation for the N-Trailer problem is presented in [785].

- Another interesting result related to Japanese researchers was reported in [821]. It became clear that a system with vision estimation for control purposes requires dealing with the structure of the image, not just with a vector of variables.
- It was about time to start a concerted effort focused upon creation of unmanned ground vehicles. The projects DEMO I and II started in 1990. In 1996 the first outline of this large project came into existence [786]. This spurred much research that produced significant results (see DEMO III in [973]). They include: development of 4D RCS methodology [495], and new methods of sensing, representation, and control that are being adopted by many organizations.
- Among the latter developments the following seem to be of serious importance:
  a) the laws of causal ordering for the distributed mobile systems were analyzed in [788];
  b) the protocols of the mobile computing for the rovers [789] were developed and mobile communication networks were studied [790];
  c) further development of localization systems for outdoor robotic vehicles [791];
  d) novel control architectures were proposed for EXECUTORS of the mobile robots under disturbances [792];
  e) an expert knowledge-based system was developed for traction control of a truck [793].
- Similar growth of research results in this area has been noticed in the activities of the mobile robotic groups abroad:
  a) a novel path tracking algorithm was developed for a wheeled mobile robot with dynamic constraints [794];
  b) a new analytical controller that contains a system of supervision and subsystems of longitudinal and lateral control is reported in [795];
  c) new versions of planners have been developed, which claim optimality, and also employ genetic algorithms [796];
  d) a novel neural network-based predictive controller was developed for mobile robot navigation [797];
  e) new linearization tools were introduced for fuzzy logic controllers for autonomous vehicles [798];
  f) stability issues in mobile vehicles with steering were analyzed and a design technique was proposed for a mobile robot with fuzzy controller [824]
  g) new "behavioral" controller was developed for a farming autonomous robot [799].
- A separate but a very important area of research is related to "auxiliary" parts of the intelligent controller for autonomous vehicles: parts related to their bodies, not to their minds. Listed here are the following results that exemplify research of this type:
  a) It is customary to consider mechanical parts of the vehicle as external to the control system. In [825] the adaptive suspension vehicle is described, where the suspension system is equipped with sensors and subordinate support systems that affect its stability and modes of operation. It is possible to anticipate that in future vehicles the mechanical parts will be equipped with sensors that form an analog of a proprioceptive subsystems in living creatures and work at all levels of controllers.
  b) For a vehicle suspension system with hydraulic actuators a special device is proposed which combines property of a valve and a sensor. This research should make a suspension system smarter [826].

c) The higher resolution details of motion control are discussed in [827] where the coordinated throttle and brake actuation is proposed.
d) Similar research is described in [828] where the problem of joint functioning for brakes and throttle is coupled with a problem of fuel optimization.
e) The engine of a vehicle should have intelligence of its own. In [829], a system of joint engine control estimation and diagnosis is described.
f) The problem of tire-road friction estimation is one of the fundamental in autonomous vehicle control. In [830] a system is described which monitors this value of friction via measuring the wheel slip.
g) The geometry of motion should be taken into account more thoroughly if one wants to receive more reliable and accurate minimum path control [918].

Intelligent Highway

The goal of an intelligent highway is a result of the reality of automotive problems in the countries with advanced economy [852]. The concept of intelligent highway is outlined in [853]. A similar set of activities in Japan is reported in [854].

One of the key elements of the intelligent highway problem is the phenomenon of traffic self-organization in particular, formation of platoons or groups of vehicles that move together as a result of complicated self-aggregation processes. The possibility of controlling the platoon formation is discussed in [855]. The authors explore the possibility of forming the traffic by using decentralized control laws as suggested in [856]. The same problem is approached in [857] by using methods of fuzzy logic control.

The transitional maneuvers are addressed in [858]. The high resolution processes of highway entry make their contribution to the overall traffic control problem [859]. The problem of lane change is analyzed in [860]. A language for dealing with the problem of collision-free navigation is proposed in [861] for autonomous mobile robots. This language reflects traffic priorities in dynamic environment.

An issue of mixed traffic is discussed in [862]. This can be considered a first step toward a really intelligent transport system. It allows for having both automatically and manually controlled vehicles on a road. Two levels are considered: the low resolution level analyzes the current scenario and infers the control objectives while the higher resolution level optimizes the control solution for the upper level objectives. In order to solve this model for mixed traffic the model attempts to mimic the behavior of human drivers in vehicle following and lane changing.

6.4 Legged Vehicles

Legged mobility is associated both with indoor- and outdoor intelligent vehicles. Legged mobility requires an intelligent control system with higher intelligence because the leg configuration is more complicated than the wheel transmission, and the model of motion (walking or jumping) is more sophisticated than the one exercised by wheeled or tracked vehicles. The Ohio State University was the pioneer of walking machines in the US [863]. The two level control system for OSU Hexapod vehicle is described in [864]. An important high resolution problem in legged vehicles is assignment of the manner of walking or "gait control". A system with automatic gait control for a quadruped is described in [865]. A larger and more

complicated machine demanded for more complicated suspension. The OSU also developed the adaptive suspension vehicle (ASV). This gigantic hexapod was successfully tested. However, the motion of the vehicle was slow, and no further research is presently conducted [866].

Of course, a development of a biped is a more challenging problem since the conditions of mechanical stability are more difficult to satisfy and the agility of walking requires for an increase in the number of degrees of freedom on the overall walking system. In [867] a simplified walking biped is discussed whose equilibrium is taken care of by controlling by potential energy conserving orbit. Apparently, it can be achieved only by introducing elements of learning [868]. Advanced results in development of the biped robot have been obtained in Nagoya University in Japan [869].

Further control solutions are being explored for the legged vehicles. In [870] a two-level control system is proposed for the quadruped robot. In [871] a self-organizing multiagent model is proposed for the folding-legged uniped robot. In [872] joint statically/dynamically stable walking processes are analyzed for the quadruped robot.

6.5 Various Media Intelligent Vehicles

Waterborne Vehicles

Control solutions for both autonomous and non-autonomous ship navigation follow the results obtained for terrain navigation [831]. Underwater vehicles have more distinctive features because their list of requirements differs from the ones formulated for terrain vehicles [832]. Nevertheless, they follow the Planner-Navigator-Pilot technical solution and most of the results can be categorized as RCS architecture [901]. More distinctions can be found in the Executor at the highest level of resolution. The mathematics of the trajectory tracking is outlined in [833]. The autopilot with reconfigurable controller is described in [834]. The tracking controller with a subsystem of prediction is described in [835].

Airborne Vehicles

The typical intelligent procedure is performed within each autopilot solution. Similar in significance, but not as wide spread operation is the formation of optimal maneuvers in optical plane. An example of the control-theoretic result is given [836]. Multiple solutions of this type are being applied and explored for STOL and V/STOL operations in special aircrafts[4]. The survey of all existing solutions that are contemplated for the intelligent flight control can be found in [837]. The intelligent parts of the controllers are divided in outer loops and inner loops. Outer loops take care of all declarative functions, inner loops are responsible for all procedural and reflexive functions. In this paper [837] the need for intelligent control is explained solely by the functions of human psychology and physiology that should be supported automatically.

A class of intelligent controllers is generated by the need to equip missiles with autopilots. At the present time the plan to follow is computed externally but the tracking is done by the autopilot [838]. A survey of unmanned aerial vehicles can be found in [975].

[4] Vertical and/or Short Take-Off And Landing (V/STOL and STOL).

Underground Vehicles

NIST experience in RCS control of mining vehicles is presented in [839]. In [840] the recent results in applying fuzzy logic and neural networks for autonomous excavation is described in [840]. The authors have thoroughly analyzed a set of salient tasks associated with the process of excavation and developed a controller that takes care of all of them. In [841] the problem of autonomous navigation is addressed for the underground mining vehicle. The system is equipped with odometry, inertial sensors including triaxial accelerometer and gyros, ultrasonic sensor and a laser sensor

Intelligent Vehicles for Space Exploration

Two types of robotic devices are associated with the space exploration problem: robots that should work in free space and planetary rovers.

SPACE ROBOTS

Intelligence systems of the first group are determined by the specifications presented in [842]. A multiplicity of research results was produced in the wake of this request. Spaceborne multilink manipulators are supposed to both move things and to move themselves [843]. The controller is designed to work under significant variation of the system parameters because of the changes in configurations. Further development of the same research is reported in [844]

PLANETARY ROVERS

CMU Robotics Institute in the 80s actively pursued rovers for Mars exploration. The legged robot Ambler is one of the results of these activities [845]. Many of explored technical solutions were similar to those recommended for the earth robots [846].

In 1987-88, Pathfinder, a broad program was outlined by NASA [847]. This program had similar sister-efforts in Europe that resulted in architectures similar to RCS [693, 848].

Brachiation Moving Devices

This area is just emerging. It is related to an unusual medium: interlaced tree branches. Brachiating Intelligent systems are supposed to move through the clutter of branches by swinging their bodies and grasping the next branch properly selected so that the "best" path is followed and safety conditions are satisfied [849]. It will be described in more detail in the section Learning in Part II of this report, because CMAC is the core part of the brachiation controller [850]. The algorithm of the brachiation controller is described in [851]. These comparatively simple devices can work successfully only if they are equipped with a good learning system (e. g. as in [884]). These issues are discussed in Part II of this report.

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